Journal of Mineral Resources Engineering, 9(2): 13-32, (2024)

Imam Khomeini International University
Vol. 9, No. 2, Summer 2024, pp. 13-32

نشریه مهندسی منابع معدنی
Journal of Mineral Resources Engineering
(JMRE)

Research Paper

Evaluation of Modern Haulage Systems Impacts on Mining Options

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Received: 09 Nov. 2023 **Accepted: 13 Apr 2024**

Abstract: In deep mines with combined mining potential, optimization hauling systems as the technological phase with the largest share in the total operation costs are essential from the aspect of achieving the profitability of the mining project. In this study, using a hybrid semi-quantitative approach, the impacts of haulage systems in large-scale and deep open-pit mines with combined mining potential were evaluated on mining options. According to the results of evaluating the use of the haulage system in the Sungun copper mine, the most appropriate haulage system was selected in-pit crushing and conveying system, truck-shovel, battery trolley, and trolley assist, respectively. Also, the use of the modern haulage system in the Sungun copper mine had a direct impact on the following mining options, respectively, with the intensity of -11.03, 32.94, 11.73, 17.06, and 15.07. (a) independent underground mining, (b) independentopen-pit mining, (c) simultaneous mining, (d) sequential mining, and (e) combinations of simultaneous and sequential. The obtained results indicate that the use of a modern and suitable haulage system for the mine leads to the desire to continue mining with the open-pit method, which leads to an increase in OTD.

Keywords: Open-pit, Underground mining, Mining options, Modern haulage systems.

How to cite this article
Badakhshan, N., Shahriar, K., and Afraei, S. (2024). *“Evaluation of modern haulage systems impacts on mining options”*. Journal of Mineral Resources Engineering, 9(2): 13-32.
DOI: 10.30479/JMRE.2024.19548.1672

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List of Acronyms	
AHP	Analytic Hierarchy Process
APR	Annual Production Rate
BT	Battery Trolley
CAPEX	Capital Expenditure
ERS	Energy Recovery System
ESG	Environmental, Social, and Governance
FIPCC	Fixed In-Pit Crushing and Conveying
FMIPCC	Internal Rate of Return
IPCC	In-Pit Crushing and Conveying
ML	Mine Life
OP	Open-Pit
OPEX	Operating Expenditure
OPL	Optimum Pit Limit
OPUG	Open-Pit and Underground
OTD	Optimum Transition Depth
SFIPCC	Semi-Fixed In-Pit Crushing and Conveying
SMIPCC	Semi-Mobile In-Pit Crushing and Conveying
TA	Trolley Assist
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
TS	Truck-Shovel
UG	Underground

1- INTRODUCTION

Today, the main issue with deep OP mines is whether to continue mining with the OP mining method or switch to one of the UG mining methods. The transition from OP mining to UG mining and determining the optimum transition depth is one of the main challenges in mines that extend from the surface to a great depth with a steep slope. Among the most important of these are those related to the promotion of technology, especially the advancement of new equipment technology, which impacts other critical factors such as economic, social, environmental, and technical. Achieving OTD in the transition operation from OP to UG mines requires considering the critical factors affecting the transition depth. Using careful evaluation, it is possible to determine the depth close to the OTD in practice [1,2].

Although many factors, such as the depth, size, and shape of the deposit body, influence the choice of mining method, mining engineers statistically traditionally tend to use the surface method whenever possible. Today, more than 90% of minerals are extracted by surface methods (OP mining, strip mining). The most important reasons for this are related to the fact that the OP method is usually more favorable and dominant than the UG method, especially in terms of recovery, production capacity, mechanization, control of grade, cutoff grade, ore loss, dilution, economics, and safety. In surface mines, load and hauling, with a share of 65-70 %, has always been a significant part of capital and operational costs. In this sense, the optimization of the load and hauling system can have a substantial impact on the mining economy. In most surface mines, a combination of trucks and shovels is most commonly used to load and haul materials. The flexibility and controllability of these systems have made them more practical. As the mines get more profound, the unloading destinations (ore and waste) become more and more distant, and the transition length increases as well as the height difference between the loading and unloading points. All this reduces the economic benefits of truck and shovel systems [3]. To overcome these costs and make mining operations profitable in this situation, there are two general solutions, which are: 1) changing the mining method from OP to UG mining; and 2) delaying the change from OP to UG by making some changes. The first solution to solve this problem is to change the mining strategy and method and move from the surface to the UG mining method. Usually, this transition from surface to UG means a significant technological change and has a great impact on the production and economics of a mining project. Due to the risk of not achieving the business goals (default or the company's business commitment) during and after this transition, most mining companies try to delay this vital change as much as possible by using alternative solutions. There are mainly two solutions: the first solution includes the purchase of equipment with more capacity (shovel and truck with high loading and hauling capacity), and the second solution includes the use of continuous production systems, low pollution, high productivity, and high compatibility with economic, environmental, and social opinion [4].

With the sharp increase in demand for minerals, deposits with high geological complexity, and dwindling high-quality resources (reduction of mineral grade), there are many challenges facing the mining section. These consist of: 1) Greater depths and lower grades: OP mining depths have significantly expanded over the last two decades. Some OP mines go down more than 1000 m in depth [3]. It is worth noting that future deposit extraction will inevitably be conducted at greater depths and lower grades compared to current practices, and this tendency is anticipated to continue. Increasing the depth of mining leads to an increase in the hauling distance, an increase in the waste removal ratio (stripping ratio) per ton of mined ore, a high depreciation of non-continuous hauling systems, an increase in the amount of diesel fuel, and a decrease in hauling efficiency per unit of time. 2) High operating cost: As mines become more profound and stripping ratios increase with a lower grade, more waste material needs to be extracted. The haulage truck fleet grows correspondingly, requiring more operators and maintenance staff and a subsequent increase in diesel fuel consumption .In addition, as copper ore grades decline, more ore needs to be processed to attain similar metal production. A decrease in copper ore grade between 0.2% and 0.4% requires seven times more energy than present-day operations. Reducing the cost of truck haulage, which makes up about half of the operating expenses of a mining operation, is now more essential than ever. 3) Fuel price volatility: Fossil fuel price volatility significantly impacts mining viability but is outside the control of most miners [5]. 4) ESG issues, geopolitics, and climate change: Huge developments and changes due to war, weather events, new governments in mining areas, and changing relationships in other regions have a significant impact on the mining section [6], and 5) the smartization (automation/dispatching) of mines with the aim of increasing work efficiency by reducing human intervention and errors:

Nowadays, most mines are looking for smartization of different parts of mining activities, especially pieces that have the potential for continuous training. Most investments in this section are made with the aim of increasing work efficiency, reducing human errors, and improving safety in mines [7].

Many studies have been done on alternative diesel haulage systems and OTD. The most critical weakness of the studies related to alternative diesel haulage systems is that they are not comprehensive and do not consider the combined mining mode in evaluating the application of alternative diesel haulage systems to OTD. The weakness of studies related to OTD is not considering the impact of alternative diesel haulage systems while determining the optimal time and place to transition from OP to UG mining. Table 1 compares the characteristics of the present study with those of other studies conducted in the field of alternative diesel haulage systems and OTD.

The innovation of the research, compared to the background of the research, is the evaluation of the impact of the use of modern haulage systems

Table 1. Studies conducted in the field of alternative diesel haulage systems and OTD

Researcher(s)	Country (Case Study)	Year	Comprehensive	OP	OP - UG	Alternative diesel	OTD	Research Focus	Commodity
Bao et al. [5]	Overall	2023	✓	✓		✓		Electrification Alternatives for OP Mine Haulage (TS, IPCC, TA, and BT systems) *	Metals
Al Habib et al. [8]	Canada	2023		✓		✓		Short-term planning of OP mines with semi-mobile IPCC	Copper
Chung et al. [9]	Australia	2022	✓	✓			✓	Timing of the transition from OP to UG mining: A simultaneous optimization model for OP and UG mine production schedules	Gold
Liu and Pourrahimian [10]	Canada	2021	✓	✓		✓		A Framework for OP Mine Production Scheduling Under Semi-Mobile IPCC Systems with the High-Angle Conveyor	Copper
Osanloo and Paricheh [11]	Iran	2020	✓	✓		✓		IPCC technology in OP mining operations	Copper
Bernardi et al. [12]	China	2020		✓		✓		Comparison of fixed and mobile IPCC and truck-shovel systems used in mineral industries through discrete-event simulation	Copper
Mohammadi et al. [13]	Iran	2020		✓		✓		Review of the IPCC system and its case study in the copper industry	Copper
Osanloo and Paricheh [14]	Iran	2019		✓		✓		In-pit crushing and conveying technology in OP mining operations: A literature review and research agenda	Copper
Nehring et al. [15]	Australia	2018	✓	✓		✓		A comparison of strategic mine planning approaches for IPCC and truck/shovel systems	Copper
King et al. [16]	Africa	2017		✓			✓	Optimizing the OP-to-UG Mining Transition	Copper
Ritter [17]	Germany	2106		✓		✓		Contribution to the Capacity Determination of Semi-Mobile IPCC Systems	Metals
Dean et al. [18]	China	2015		✓		✓		Selection and Planning of Fully Mobile IPCC Systems for Deep OP Metalliferous Applications	Metals
Tavakoli Mohammadi et al. [19]	Iran	2011	✓	✓		✓		Review of the system and its case study in the copper industry	Copper
Morriss [20]	Snowden	2008		✓		✓		Key production drivers in IPCC studies	Iron

* TS: Truck-Shovel, IPCC: In-Pit Crushing and Conveying, TA: Trolley Assist, and BT: Battery Trolley.

on the mining options in deposits with high depth and combined extraction potential. According to the review of previous studies, this is the first study that examines the impact of these systems on mines with the potential of combined OP-UG mining and deposits in great depth.

In Table 2, the types of loading systems in OP mines are stated along with their specifications, advantages, and disadvantages. Also, a comparison between types of haulage systems in mines is presented in Table 3. To achieve optimum decision-making in mining haulage systems, it is necessary to use the mining system analysis method for evaluating each mining system parameter in Table 3.

According to Table 3, diesel TS shows the best

Table 2. Types of hauling systems in OP mines along with their specifications, advantages, and disadvantages [5,11,13]

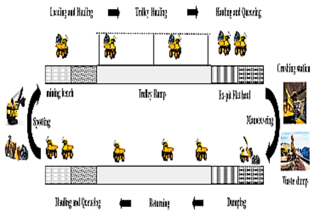
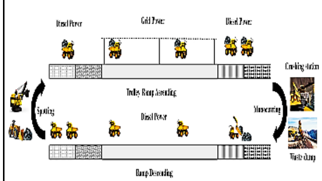
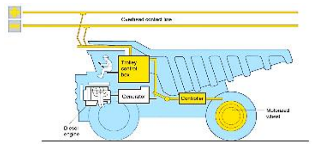
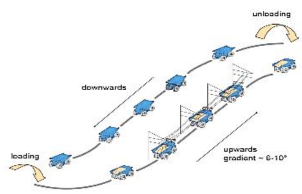
Type of hauling device	Classification	favorable conditions of use	Features/ specifications	Advantages	Disadvantages	Sample
BT systems combined with autonomous battery-electric trucks and ERSs	Dynamic charging BT systems Stationary charging BT systems Dual trolley BT systems	The need to reduce pollutants, the availability of cheap electric power, and the high price of fuel	Battery Trolley aims to offer a haulage mining system using the full source of electrical power as a decarburization technology through autonomous high-intensity battery-electric trucks, TA systems, and energy recovery systems.	1. High safety; 2. Energy saving; 3. Operational improvements; 4. BT systems can take advantage of autonomous trucks from both safety and productivity perspectives; 5. Decarburization; 6. Reducing energy costs; 7. Lower maintenance costs; and 8. The operating costs of BT are less than the conventional diesel truck fleet because it uses electricity as end-use energy, which is similar to IPCC.	Despite the advantages associated with BT, decision-makers may be reluctant to use it for some reasons. From diesel-electric to battery-electric power, this transition would significantly increase the mine's electricity cost and demand, power infrastructure, and station capital expenditure. Additionally, the battery truck fleet has to face many challenges, such as battery size and performance, high upfront capital outlay, feasibility, availability, capability, truck fleet dispatching, mine design restrictions, and ancillary equipment maintenance schedule arrangement.	
IPCC (combination of feeding, crushing, conveying, and discharging methods)	FIPCC SMIPCC SFIPCC FMIPCC	Suitable for high production rate (above four mtpa), life of more than ten years, and distance of more than 2 km	The IPCC system comprises a combination of feeding, crushing, conveying, and discharging systems.	1. Lower operating, maintenance and energy costs; 2. Ideal for steep OP mines; 3. Less installed power compared to trucks; 4. Less gas emissions; 5. Less road maintenance; and 6. Less dust, noise, and water usage.	1. High capital costs; 2. A final pit wall is required; and 3. A max lump size of 250 mm.	
TA	electric trolley	1. Global crises related to fuel; 2. Environmental sensitivities; 3. An increase in fuel prices.	TA systems consist of three subsystems: power supply to the pit, overhead power distribution, and trucks with TA capability.	1. Reducing CO2 and greenhouse gas emissions; 2. Reducing mining accidents; 3. Reducing diesel fuel consumption; 4. Improving productivity; 5. Increasing engine and wheel motor life; 6. Reducing fleet size; 7. Lowering maintenance costs; and 8. Lowering overall operating costs.	1. High upfront capital outlay; 2. Mine design and planning restrictions; 3. Trolley Assist system maintenance; 4. System capacity; 5. Access to electricity; and 6. Operator requirements.	

Table 2 (Continued). Types of hauling systems in OP mines along with their specifications, advantages, and disadvantages [5,11,13]

Type of hauling device	Classification	favorable conditions of use	Features/ specifications	Advantages	Disadvantages	Sample
Truck trolley systems	electric trolley haulage	When environmental sensitivities (relative to pollutants) are high, access to diesel fuel is complex, and its price is high, it is a suitable alternative for diesel trucks.	1. Capacities up to 345 tonnes; 2. The truck trolley system is most cost-effective on the ramps, where the most energy is required. The truck trolley system has the highest benefits when driving uphill on a 6 to 10-degree ramp. The rest of the haulage route, i.e., flat areas and downhill ramps, will be powered by a diesel engine.	1 .High flexibility and reliability; 2. Low capital costs; 3. Compatible with all types of material; 4. Possibility to mine selectivity; 5. Fewer emissions due to the substitution of diesel fuel with electricity; 6. Higher uphill speed, which leads to shorter cycle times; and 7. Extension of the interval between engine overhauls.	1. High operational costs; 2. Labor intensive; 3. Mine roads need to be maintained; 4. Inefficiency due to the travelling empty trucks; and 5. Extra investment due to the installation of the trolley line system.	
	Battery trolley haulage					
TS systems (Conventional truck haulage)	Dump Trucks	Hauling distance of less than 3 km Production less than 200 tons per hour	1. Capacities up to 450 tons.	1. High flexibility and reliability; 2. Low capital costs; 3. Compatible with all types of materials; 4. Possibility to mine selectively; 5. Opportunity to mine selectively; and 6. Outsourcing is possible.	1. High operational costs; 2. Labor intensive; 3. Mine roads need to be maintained; 4. Inefficiency due to the travelling of empty trucks; and 5. High level of diesel emissions.	
	Floor dump truck boxes					
	Side dump truck boxes					

performance in flexibility, CAPEX, refuelling, reliability, scalability, and capability. This explains why classic TS is prevalent in all kinds of greenfield and brownfield mining projects. IPCC can mitigate the TS disadvantages from energy efficiency, maintenance, refuelling, emissions, heat generation, and environmental footprint points. However, flexibility, CAPEX, reliability, scalability, and capability characteristics are the constraints for IPCC, especially FMIPCC, in large-scale applications at mine sites. Due to diesel-electric power and trolley limitations, TA shows medium performance in almost all parameters. In the dynamic charging alternative, because the onboard battery energy source is from grid charging uphill and energy capture downhill, the battery-electric trucks cannot complete one haul cycle without enough trolley lines setting. Therefore, dynamic charging BT has lower flexibility, reliability, scalability, and capability compared with stationary setting BT. At the same time, no recharging/swapping battery need in the battery station is the most significant merit of dynamic charging BT systems. Because of flexibility limitations and considerable capital outlay, dual-trolley BT is unlikely to be popular in large-scale BT deployment. However, double trolley BT suits some unique mine site conditions, like super-depth copper mines [5].

The purpose of this research is to evaluate and determine the relationship between the use of contemporary haulage systems in mines with the optimum transition depth from OP to UG mining and the impact of each of the modern haulage systems on the transition depth. For this purpose, a hybrid semi-quantitative approach was used for evaluation.

Table 3. Comparison between diesel TS, IPCC, TA, and BT [5]

Parameter	Diesel TS	SMIPCC/ SFIPCC	FMIPCC	TA	Dynamic charging BT	Stationary charging BT	Dual trolley BT
Flexibility	High	Medium	Low	Medium	Low	Medium	Medium
Energy efficiency	Low	Medium	High	Medium	High	High	High
CAPEX	Low	High	High	High	High	High	High
OPEX	High	Medium	Low	Low	Low	Low	Low
Maintenance requirements	High	Medium	Low	Medium	Medium	Medium	High
Service life	Short	Medium	Long	Long	Long	Long	Long
Additional infrastructure	No	No	No	Yes	Yes	Yes	Yes
Refueling/Recharging/Swapping	Fast	None	None	Fast	None	Low	Low
Emissions	High	Low	None	Low	None	None	None
Heat generation	High	Medium	Low	Medium	Low	Low	Low
Environmental footprint (Noise/Dust/DPM/Vibration)	High	Medium	Low	Medium	Low	Low	Low
Reliability	High	Medium	Low	Medium	Low	Medium	Low
Scalability	High	Low	Low	Medium	Low	Medium	Low
Capability	No	Yes	Yes	Yes	Yes	Yes	Yes
Safety	Low	Low	Medium	Low	Medium	Medium	Medium

The main goal of this research is to determine how the use of modern haulage systems affects different mining options in deposits with combined mining potential.

2- METHODOLOGY

2-1- Case study: Sungun copper mine

In this research, Sungun copper mine is chosen as a case study because new exploration indicates the deep expansion of high-grade reserves that have the potential for combined OP and UG mining. Also, the Sungun copper mine is one of the largest copper mines in Iran and has about 3 billion tons of copper ore reserves with an average grade of 0.5%. In the Sungun copper mining complex, the evaluations are that OP production in the coming years will be more economical to continue extracting the reserve with the UG method of block caving due to economic and environmental reasons [21]. Currently, primary studies are focused on determining the time of the initial undercutting of the destructive section. It is predicted that the UG part of the block destruction of Sungun copper mine will become the leading UG mine in Iran in the coming decades. The Sungun copper mine is one of the biggest OP and critical copper mines in Iran, and the Centre East, which is found 105 km northeast of Tabriz, 75 km northwest of Ahar, and 28 km north of Varzeqan, borders Azerbaijan and Armenia countries. Figure 1 shows the location of the Sungun copper mine [22].

2-2- Steps to evaluate the impacts of modern haulage systems on OTD

As mentioned earlier, the use of qualitative methods only for the review and evaluation of different projects is not very accurate. For this reason, there is a need to try to create and apply mathematical techniques to assess other projects. Based on this, the semi-quantitative-qualitative method has been used to assess the impacts of modern haulage systems on mining options based on quantitative and mathematical methods. This research, using field surveys and the opinions of mining experts (especially those who are involved in transition issues from OP to UG mining and have sufficient technical knowledge and experience in this field), seeks to evaluate the impacts of modern haulage systems on mining options. The present research examines mines with the potential of combined OP-UG mining.

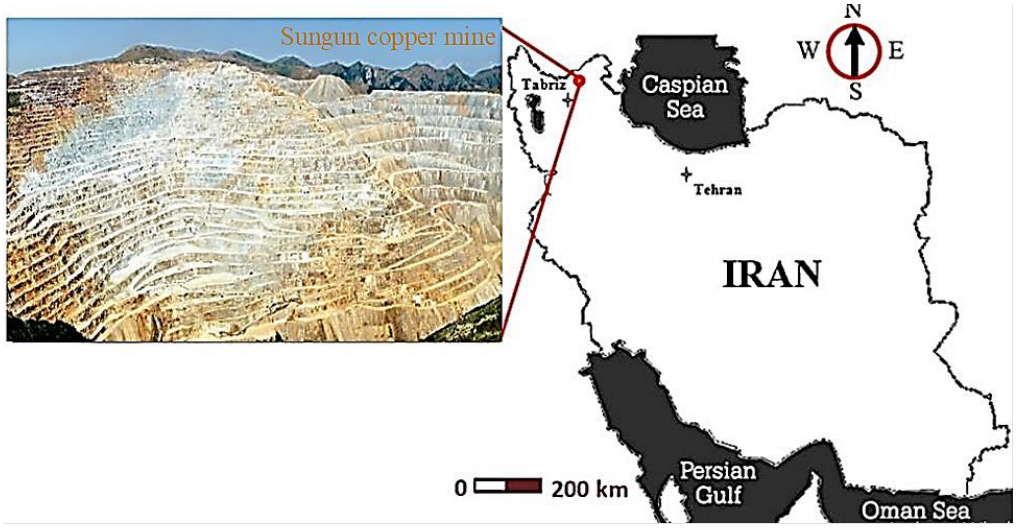


Figure 1. Location of the Sungun copper mine [22]

In metal deposits that have a significant slope and depth expansion, the mining of the deposit is first started with surface mining methods (mainly OP). As the mine gets deeper, the stripping ratio of the tonnage of waste removed per one ton of ore reaches such a size that mining by other surface methods has no economic, environmental, and social (The increase in waste removal causes an increase in adverse environmental effects, which leads to an increase in social opposition.) justification. After this depth, if the reserve is suitable for volume and grade, mining continues using UG methods. The most critical issue, in this case, is determining the "optimum transition depth from OP to UG mining." Companies usually believe that the OP mining method will continue until it is economically viable and then start UG mining. This approach results from the idea that the economic pit of the mine, along with the OP mining equipment and experienced human resources, should not be challenged as much as possible. One of the most important positive factors affecting this approach is the use of modern haulage systems, which have been studied and investigated by many large-scale deep OP mines worldwide. In this research, four haulage systems in OP mines that have the potential to be used in mining were determined: TS, IPCC, TA, and BT. Then, to select the most suitable haulage system among these four systems in the Sungun copper mine, 30 specified factors and the TOPSIS method were used. These 30 factors were determined based on previous studies, field research, and surveying of large-scale OP mine haulage systems around the world. Also, five alternative modes related to the mining options were determined and considered based on the optimum transition depth, which consists of: (a) independent OP mining; (b) independent UG mining; (c) simultaneous OPUG with and, or without a crown pillar; (d) sequential OPUG mining without a crown pillar, and (e) combinations of simultaneous and Sequential OPUG mining without a crown pillar. In this research, first by studying the research conducted in the field of modern haulage systems and field surveys of several mines with the potential for combined extraction in Iran, 30 influential factors in choosing the haulage system in Sungun copper mine were selected. In addition, 30 criteria related to mining options (6 items each) were determined and identified. On the basis of the scoring of each of the 30 primary factors based on the experts' opinions and using the TOPSIS method, 10 essential and high-impact main factors were selected (Questionnaire No. 1 sent to experts). In addition, scoring scenarios were defined for each of the 10 factors (Questionnaire No. 2 was sent to experts). The reasons that led to the use of the TOPSIS method in this part of the research are as follows: 1) This method is one of the compensatory methods. That is, the weight of all options and criteria is involved in decision-making, and no weight is ignored in this method;2) The TOPSIS method has appropriate mathematical foundations; 3) The output of the system is quantitative, and in addition to determining the best option, the ranking of other options is expressed numerically; 4) To determine the best option, a significant number of criteria can be examined; 5) Decision-making is possible if there are positive and negative criteria (even together in the same issue); 6) In the TOPSIS method, qualitative criteria can be quantified easily, and decision-making is possible despite qualitative and quantitative criteria. Next, pairwise comparison, the weighting of the criteria, and then their analyses using the AHP method were made (Questionnaire No. 3 wassent to experts). In this part of the research, for reasons such as: 1) transforming a complex problem in the form of hierarchical principles and actually opening the problem; 2) simultaneous analysis and evaluation of quantitative and qualitative criteria; and 3) comparative decision-making and comparisons, the AHP method was used twice. The correlation matrix and the impact between the factors and criteria were established, and the range of changes was determined for each element. Finally, the final score of the effect of using a selected haulage system on mining options in large-scale and deep OP mines that have the potential for combined mining was determined. The modern haulage systems impact evaluation steps on mining options are clearly shown in the flowchart in Figure 2.

3- Results (findings)

3-1- Determining and identifying the primary factors and criteria

According to the studies they have carried out related to the problem of modern systems on mining options, using the knowledge and experiences of the personnel of mines with the possibility of combined mining and field visits and surveys of some mines with the potential of combined mining, such as Sarcheshmeh and the Sungun copper mines, 30 of the important factors affecting the use of haulage systems on the transition depth in large-scale deep OP mines with mining potential were selected (Table 4). Also, based on these 30 criteria, mine conditions,

Table 4. 30 influential factors in choosing the haulage system in Sungun copper mine [Researcher's reviews]

Parameters	Symbol
OPEX	F_1
CAPEX	F_2
Flexibility	F_3
Energy efficiency	F_4
Environmental footprint (noise and dust)	F_5
CO2 and diesel particular emissions	F_6
Annual production rate	F_7
Mine life	F_8
Safety	F_9
Government laws and related restrictions	F_{10}
The existence of technical and operational knowledge	F_{11}
Hauling distance	F_{12}
Dependence on weather conditions	F_{13}
Environmental laws and sensitivities	F_{14}
Social sensitivities	F_{15}
Mining scale	F_{16}
Availability of different energies	F_{17}
implementation	F_{18}
scalability	F_{19}
Lack of skilled workforce	F_{20}
Energy price volatility	F_{21}
Maintenance	F_{22}
Production efficiency	F_{23}
Reliability	F_{24}
Material requirements	F_{25}
Compatible with all types of materials	F_{26}
Possibility of selective mining	F_{27}
Service Life	F_{28}
Refueling/Recharging/Swapping	F_{29}
Heat Generation	F_{30}

and the four haulage systems considered in this research, the most suitable haulage system was selected. In addition, ten measures related to the selected. In addition, ten measures related to mining options, which are affected by the main factors, were determined and identified according to Table 5, which are affected by the main factors, were determined and identified

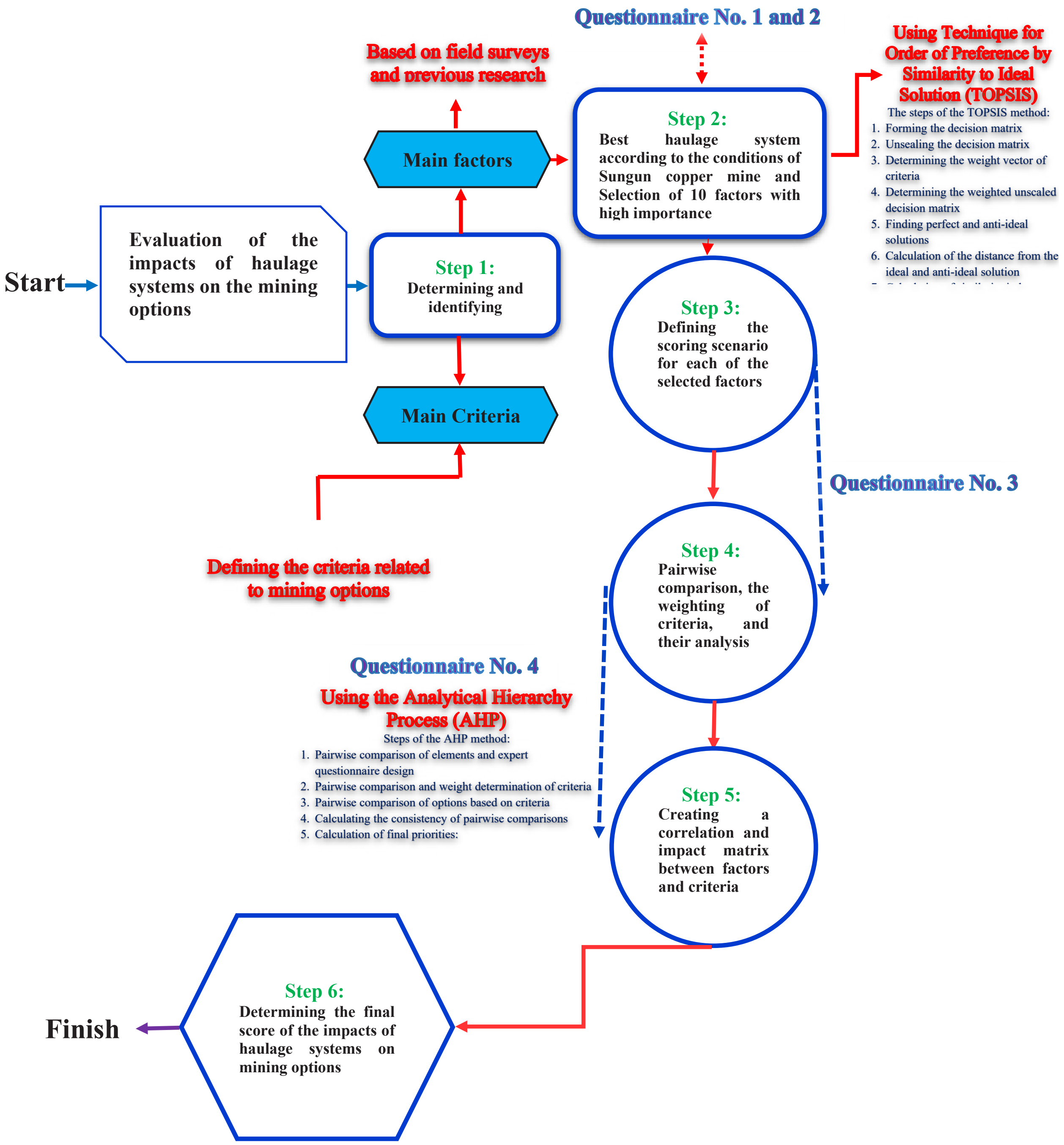


Figure 2. The stages of evaluation of the impacts of haulage systems on mining options

Table 5. Criteria considered in this research [Researcher's reviews]

Criteria	Sub-criteria	Symbol
Independent OP mining	UPL and OPL	C_1
	Production rate and productivity (OP)	C_2
	Cutoff grade (OP)	C_3
	Mine life (OP)	C_4
	Maximum use of OP mining facilities and equipment	C_5
	Mineable ore tonnage (OP)	C_6
Independent UG mining	Maximum mining depth (UG)	C_7
	Mining area border (UG)	C_8
	Mine life (OP)	C_9
	Production rate and productivity (UG)	C_{10}
	Mineable ore tonnage (UG)	C_{11}
	Cutt-off grade (UG)	C_{12}
Simultaneous OPUG mining with or without a crown pillar	OTD (simultaneous OPUG)	C_{13}
	Maximum mining depth (simultaneous OPUG)	C_{14}
	Mining area border (simultaneous OPUG)	C_{15}
	Mine life (simultaneous OPUG)	C_{16}
	Mineable ore tonnage (simultaneous OPUG)	C_{17}
	Production rate and productivity (simultaneous OPUG)	C_{18}
Sequential OPUG mining without a crown pillar	OTD (sequential OPUG)	C_{19}
	Maximum mining depth (sequential OPUG)	C_{20}
	Mining area border (sequential OPUG)	C_{21}
	Mine life (sequential OPUG)	C_{22}
	Mineable ore tonnage (sequential OPUG)	C_{23}
	Production rate and productivity (sequential OPUG)	C_{24}
Combinations of simultaneous and Sequential OPUG mining without a crown pillar	OTD (simultaneous and sequential)	C_{25}
	Maximum mining depth (simultaneous and sequential OPUG)	C_{26}
	Mining area border (simultaneous and sequential OPUG)	C_{27}
	Mine life (simultaneous and sequential OPUG)	C_{28}
	Mineable ore tonnage (simultaneous and sequential OPUG)	C_{29}
	Production rate and productivity (simultaneous and sequential OPUG)	C_{30}

according to Table 5.

3-2- Selection of 10 factors with high importance and a suitable haulage system

The scoring method for each of the 30 initial factors to select ten critical factors in using haulage systems in mines with combined OP and UG mining potential and continuing to work with those ten factors (Questionnaire No. 1 sent to experts) was based on Table 6.

To make an accurate assessment, the opinions

Table 6. How to score the factors to determine the most important ones

Importance	Score assigned
unimportant	1
Very low	2
Low	3
medium	4
High	5
Very high	6
very important	7

of 31 experts with sufficient technical knowledge and field experience were used in this research. Out of these 31 experts, 18 specialize in extraction, 4 in the environment, 4 in processing, 3 in exploration, and 2 in economics.

The average scores of experts to Questionnaire 1 to determine the ten important, influential factors are according to Table 7.

Table 7. Average scores of experts in Questionnaire 1 to determine ten important influential factors

Parameters	Score assigned	Symbol
OPEX	6.08	F_1
CAPEX	6.13	F_2
Flexibility	5.94	F_3
Energy efficiency	4.93	F_4
Environmental footprint (noise and dust)	5.64	F_5
CO2 and diesel particular emissions	5.01	F_6
Annual production rate	5.33	F_7
Mine life	5.14	F_8
Safety	4.46	F_9
Government laws and related restrictions	4.03	F_{10}
The existence of technical and operational knowledge	4.67	F_{11}
Hauling distance	6.34	F_{12}
Dependence on weather conditions	3.84	F_{13}
Environmental laws and sensitivities	4.14	F_{14}
Social sensitivities	3.21	F_{15}
Mining scale	5.07	F_{16}
Availability of different energies	4.76	F_{17}
implementation	4.03	F_{18}
scalability	3.74	F_{19}
Lack of a skilled workforce	3.21	F_{20}
Energy price volatility	4.89	F_{21}
Maintenance	4.86	F_{22}
Production efficiency	5.87	F_{23}
Reliability	3.94	F_{24}
Material requirements	3.47	F_{25}
Compatible with all types of materials	4.65	F_{26}
Possibility of selective mining	3.08	F_{27}
Service Life	4.96	F_{28}
Refuelling/Recharging/Swapping	3.11	F_{29}
Heat Generation	2.91	F_{30}

To rank the factors and determine ten crucial factors based on experts' opinions, the TOPSIS method was used. The results of this ranking are shown in Table 8. The continuation of work and evaluations were done based on ten factors related to ranks 1-10.

Based on 30 criteria, mine conditions (Questionnaire No. 2 sent to experts), and four haulage systems considered in this research, the most suitable haulage system was selected (Table 9).

According to the results of Table 9, the most suitable haulage systems in Sungun copper mine are IPCC, TS, BT, and TA, respectively.

3-3- Defining the scoring scenario for each of the selected factors

The definition of the scoring scenario for each of the ten primary factors according to different conditions and their impact (Questionnaire No. 3 sent to experts), along with the average scores (according to the values in Table 10), are given in Table 11.

3-4- Pairwise comparison, the weighting of criteria, and their analysis with AHP

Pairs were compared, and the criteria were weighed and then analyzed using the analytical hierarchy process method (Questionnaire No. 4 sent to mining experts). This questionnaire

Table 8. Ranking results of influential factors

Parameters	Symbol	Rank
Hauling distance	F_{12}	1
CAPEX	F_2	2
OPEX	F_1	3
flexibility	F_3	4
Production efficiency	F_{23}	5
Environmental footprint (noise and dust)	F_5	6
Annual production rate	F_7	7
Mine life	F_8	8
Mining scale	F_{28}	9
CO2 gas emission	F_6	10

Table 9. Selection of a suitable haulage system for the Sungun mine using the TOPSIS method (according to 30 specified factors)

Haulage system	Distance from the ideal solution	Distance from anti-ideal solution	Similarity index
TS	0.1003	0.0997	0.5015
IPCC	0.1014	0.0924	0.5232
BT	0.1101	0.1460	0.4300
TA	0.1008	0.1324	0.4322

shows the importance of each index over the others. Numbers are selected from 1, 3, 5, 7, and 9. In this scoring, the number 9 indicates that the importance of the factor is much greater than the factor with which it is compared, and the number 1 means that both aspects are equally important. The average scores given by mining experts are shown in Table 12.

After forming a pairwise comparison matrix between the criteria, each row was divided into the sum of the column values. Finally, the relative importance of the criteria was obtained by calculating the sum of the row values (the AHP method). Table 13 shows the weight of each of the standards.

3-5- Creating a correlation and impact matrix between factors and criteria

The impact factors on sustainable development components are given as (VH) very high impact, (H) high impact, medium impact (M), low impact (L), very low impact (VL), and affectless (Z). To score the questionnaires, the experts gave a score of 0 for the influential factor, 2 for very low impact, 4 for low impact, 5 for medium impact, 7 for high impact, and 9 for very high impact. In the following, the average points given by the experts to the ten selected factors according to the scenarios that were defined for each of these impact factors (10x1 matrix) were multiplied in the weighted values matrix of the factors influencing the components of sustainable development (1x10 matrix), and a sustainable development evaluation matrix was obtained.

The resulting sustainable development evaluation matrix was normalized. Next, the weights obtained using the AHP method (in the form of a diagonal matrix) were multiplied by the normalized matrix. The weighted normalized correlation matrix was obtained according to Table 14.

Table 10. How to score the factors based on their impact

The extent of the impact	Score assigned
Affectless	1
Very low impact	2-3
low impact	4-5
medium impact	6-7
High impact	8-9
Very high impact	9-10

3-6- Score of Mining options criteria (worst case)

The transcript of the scoring scenario for each of the ten principal factors is multiplied by the weighted standard correlation matrix, assuming the highest score (10), which becomes a 1-in-10 matrix. In this case, the maximum score of each Mining options criterion (worst-case) is obtained according to Table 15. Considering the relative weight of the factors influencing the evaluation matrix, the maximum score of each Mining options criterion (worst case) is different. Therefore, the scores of mining options criteria are not comparable. Therefore, by calculating the relative score of each bar based on the maximum impact score, the real impact intensity is obtained. With this type of output from the evaluation matrix, the estimated impact power on each Mining options criterion can be compared to the maximum impact intensity. The elements of Table 15 show the severity of the effects of using haulage systems on each measure of mining options, and the values close to 100% (with a direct relationship) show

Table 11. The importance of influential factors for an ideal mine with standard conditions and a case study (Sungun copper mine)

Factors	Possible options	Score range	Average score	Symbol
Hauling distance	D > 2 km	10 ≤S≤ 9	9.31	F_{12}
	D = 1-2 km	8 ≤S< 9		
	D <1km	7 ≤S< 8		
CAPEX	low	10 ≤S≤ 8	4.32	F_2
	medium	4 ≤S< 8		
	high	1 ≤S< 4		
OPEX	low	10 ≤S≤ 6	8.16	F_1
	medium	4 ≤S< 6		
	high	1 ≤S< 4		
Flexibility	Very low	10 ≤S≤ 6	3.84	F_3
	medium	4 ≤S< 6		
	Very high	1 ≤S< 4		
Production efficiency	Very high	10 ≤S≤ 8	8.61	F_{23}
	medium	4 ≤S< 8		
	Very low	1 ≤S< 4		
Environmental footprint (noise and dust)	Very high	1 ≤S< 4	8.73	F_5
	medium	4 ≤S< 8		
	Very low	10 ≤S≤ 8		
APR	APR > 56 Mtpa	8 ≤S≤ 10	8.86	F_7
	14 Mtpa ≤ APR < 56 Mtpa	5 ≤S< 8		
	7 Mtpa ≤ APR < 14 Mtpa	3 ≤S< 5		
	APR < 7 Mtpa	1 ≤S< 3		
ML	ML > 30	5 ≤S≤ 10	9.04	F_8
	ML < 30 year	1 ≤S< 5		
Mining scale	Large-scale mining (LSM)	10 ≤S≤ 8	9.21	F_{28}
	Medium-scale mining (MSM)	4 ≤S< 8		
	Small-scale mining (SSM)	1 ≤S< 4		
CO2 gas emission	low emission of CO2 gas	1 ≤S< 5	4.75	F_6
	High emission of CO2 gas	5 ≤S≤ 10		

favorable conditions for the sub-criteria of mining options if haulage systems are used. Conversely, the closer the number is to 100%, the more unfavorable the conditions are for the mining option and its sub-criteria.

The relative score of each mining option index that shows the overall impact of using haulage systems on that index, based on the results of Table 15, according to equations 1 to 5, is equal to:

$$Independent\ OP\ mining = \frac{Total\ sub - criterion\ score}{Number\ of\ sub - \text{criteria}} = \frac{197.63}{6} = 32.93833333 \quad (1)$$

$$Independent\ UG\ mining = \frac{Total\ sub - criterion\ score}{Number\ of\ sub - \text{criteria}} = \frac{-67.81}{6} = -11.30166667 \quad (2)$$

$$Simultaneous\ OPUG\ mining\ With\ and, or\ without\ crown\ pillar = \frac{70.4}{6} = 11.73333333 \quad (3)$$

$$Sequential\ OPUG\ mining\ without\ crown\ pillar = \frac{102.34}{6} = 17.05666667 \quad (4)$$

$$Combinations\ of\ simultaneous\ and\ Sequential\ OPUG\ mining\ without\ crown\ pillar = \frac{90.39}{6} = 15.065 \quad (5)$$

To determine the overall effect of using haulage systems technology on the transition depth (mining option) and compare the results of the evaluation matrix of the mining option, the final relative score, or “relative overall impact score”, is calculated according to Equation 6.

$$Creative\ impacts\ of\ the\ score = \frac{32.94 - 11.03 + 11.73 + 17.06 + 15.07}{5} = 13.154 \quad (6)$$

Table 12. Average scores (geometric average) given by experts (scores from 1 to 9)

	F_{12}	F_2	F_1	F_3	F_{23}	F_5	F_7	F_8	F_{28}	F_6
F_{12}	1	5.263	7.343	4.263	5.543	6.573	4.423	7.313	8.123	6.153
F_2	0.1900	1	5.493	2.223	2.043	4.243	3.133	5.653	4.073	4.103
F_1	0.153	0.193	1	3.353	2.253	3.013	1.893	3.253	2.613	1.033
F_3	0.253	0.463	0.313	1	2.243	1.453	1.683	1.883	2.233	2.333
F_{23}	0.193	0.503	0.463	0.463	1	0.823	3.233	2.883	1.563	1.683
F_5	0.163	0.253	0.343	0.703	1.243	1	2.883	3.133	1.413	1.913
F_7	0.143	0.333	0.543	0.613	0.323	0.363	1	5.453	2.353	2.093
F_8	0.153	0.323	0.323	0.543	0.363	0.333	0.193	1	0.883	1.563
F_{28}	0.133	0.393	0.393	0.463	0.663	0.723	0.443	1.163	1	1.553
F_6	0.173	0.993	0.993	0.443	0.613	0.543	0.493	0.663	0.663	1

Table 13. The relative weight of criteria using the AHP method

Factors	The relative weight of the criteria	Rank
F_{28}	0.294	1
F_8	0.242	2
F_1	0.101	3
F_5	0.086	4
F_6	0.073	5
F_{23}	0.064	6
F_2	0.062	7
F_{12}	0.055	8
F_7	0.037	9
F_3	0.025	10

Table 14. Weighted normalized correlation matrix

I / F	Independent OP mining						Independent UG mining					
	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}
F_{28}	15.8637	27.7757	6.9287	27.7757	27.7757	21.8197	21.8197	21.8197	12.8857	21.8197	15.8637	27.7757
F_8	12.3927	12.3927	0.9727	7.3167	12.3927	7.3167	6.0477	7.3167	9.8547	0.9727	7.3167	7.3167
F_1	3.4727	4.1867	4.1867	3.4727	4.1867	2.4007	2.4007	2.7577	2.7577	2.7577	3.4727	2.4007
F_5	3.6027	3.6027	3.0187	2.4337	3.6027	3.0187	3.0187	2.1417	3.0187	2.4337	2.1417	2.1417
F_6	2.5787	2.9797	2.5787	4.5857	4.5857	3.7827	2.9797	2.9797	0.9727	2.9797	2.5787	2.9797
F_{23}	2.6287	3.0417	2.6287	4.6977	4.6977	3.8697	3.0417	3.0417	2.6287	3.0417	2.6287	3.0417
F_2	2.3577	2.7037	2.7037	3.3967	4.0887	4.0887	4.0887	2.3577	0.9727	3.3967	1.6647	2.3577
F_{12}	2.3307	2.3307	2.3307	2.3307	0.9727	1.6517	0.9727	3.3487	2.6697	2.3307	3.3487	3.3487
F_7	3.2307	3.2307	2.2627	3.8767	3.8767	3.2307	3.2307	3.2307	3.2307	3.2307	2.5857	3.2307
F_3	0.9727	2.0267	2.0267	2.4487	2.8707	2.8707	2.8707	0.9727	1.8167	2.4487	1.3947	1.8167

I / F	Simultaneous OPUG mining with or without a crown pillar						Sequential OPUG mining without a crown pillar						Combinations of simultaneous and sequential OPUG mining without a crown pillar					
	C_{13}	C_{14}	C_{15}	C_{16}	C_{17}	C_{18}	C_{19}	C_{20}	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	C_{26}	C_{27}	C_{28}	C_{29}	C_{30}
F_{28}	21.8197	15.8637	15.8637	21.8197	21.8197	21.8197	12.8857	6.9287	27.7757	21.8197	21.8197	15.8637	21.8197	21.8197	12.8857	12.8857	15.8637	27.7757
F_8	9.8547	9.8547	6.0477	12.3927	7.3167	12.3927	7.3167	7.3167	7.3167	6.0477	7.3167	12.3927	9.8547	7.3167	7.3167	7.3167	6.0477	6.0477
F_1	2.7577	2.7577	2.4007	2.4007	2.4007	1.6867	0.9727	3.4727	3.4727	2.7577	4.1867	2.4007	3.4727	2.7577	2.4007	2.4007	2.4007	2.7577
F_5	2.1417	2.1417	2.1417	2.4337	2.1417	2.1417	2.1417	3.0187	3.0187	3.0187	3.6027	2.4337	3.6027	2.1417	2.1417	0.9727	2.4337	3.6027
F_6	2.5787	0.9727	0.9727	2.5787	3.7827	3.7827	2.5787	2.5787	2.5787	2.5787	2.5787	0.9727	2.5787	2.9797	0.9727	2.5787	2.5787	2.5787
F_{23}	2.6287	2.6287	2.6287	2.6287	3.8697	3.8697	2.6287	2.6287	2.6287	2.6287	0.9727	2.6287	2.6287	3.0417	1.8007	0.9727	0.9727	0.9727
F_2	2.3577	1.6647	1.6647	0.9727	2.3577	0.9727	2.3577	2.3577	2.3577	2.7037	2.3577	2.3577	2.7037	0.9727	2.3577	2.3577	2.3577	2.7037
F_{12}	3.3487	2.6697	2.6697	2.3307	2.3307	3.3487	2.6697	2.3307	2.3307	2.3307	2.3307	3.3487	2.6697	2.3307	2.3307	0.9727	2.3307	2.3307
F_7	2.5857	2.2627	2.2627	3.2307	3.2307	3.8767	2.2627	0.9727	2.2627	2.2627	0.9727	3.2307	2.5857	2.5857	2.2627	2.2627	2.2627	2.5857
F_3	1.8167	1.3947	1.3947	1.8167	1.8167	1.3947	0.9727	1.8167	1.8167	2.0267	1.8167	1.8167	2.0267	1.8167	0.9727	1.8167	0.9727	2.0267

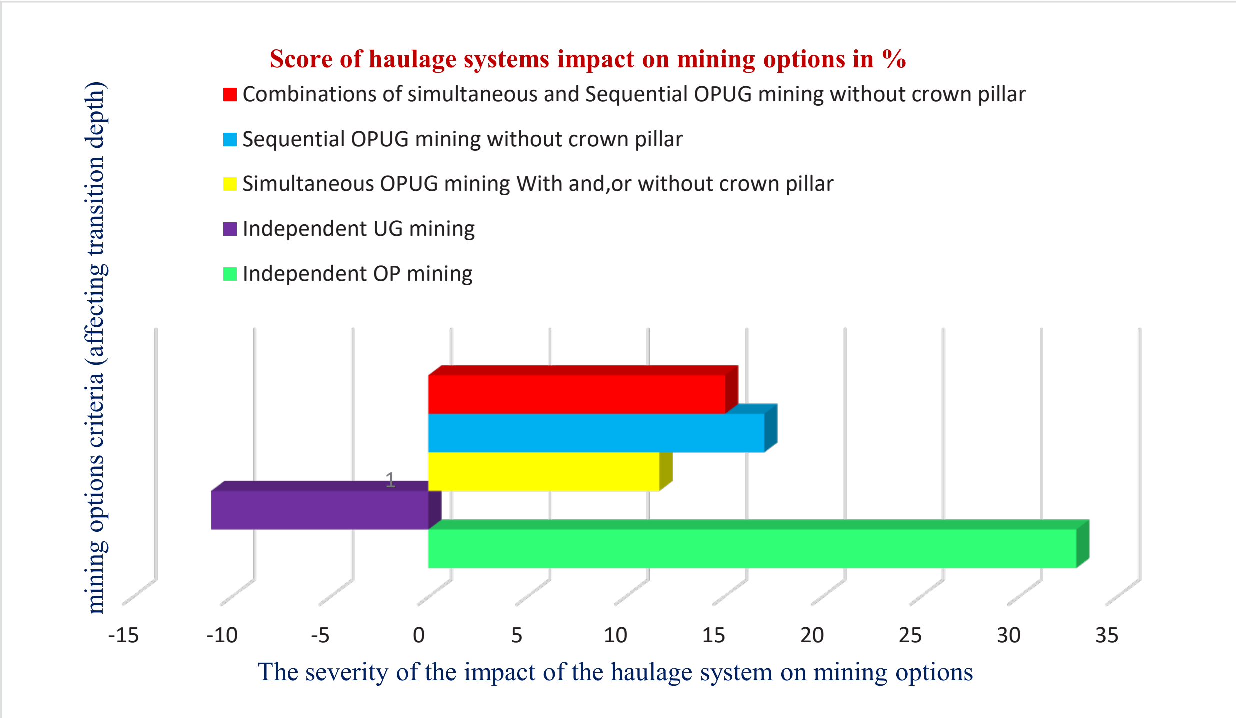


Figure 3. The effects of haulage systems on mining options

The impacts of the haulage system mining option are shown in the bar chart in Figure 3.

According to the bar chart in Figure 3, the use of haulage systems in mines has a positive impact on the use of independent OP mining and combined mining in different modes. This means that the use of modern haulage systems has a direct (positive) impact on increasing the transition depth and continuing OP mining. This is despite the fact that the use of modern haulage systems has an inverse (negative) effect on using the OP method and changing the method to UG mining.

4- CONCLUSIONS

In metal deposits that have a significant slope and depth expansion, the mining of the deposit is first started with surface mining methods (mainly OP). As the mine deepens, the ratio of the tonnage of tailings extracted per one ton of mineral material reaches such a level that mining by other surface methods has no economic, social, or environmental justification. After this depth,

Table 15. The maximum score per mining options criterion (worst case scenario) and the severity of the impact of the using haulage systems on mining option and its sub-criteria

Independent OP mining	UPL and OPL	66.53 (Direct relation)	High
	Production rate and productivity (OP)	33.52 (Direct relation)	Medium
	Cut-off grade (OP)	76.23 (inverse relation)	Very High
	Mine life (OP)	54.34 (Direct relation)	High
	Maximum use of OP mining facilities and equipment	43.24 (Direct relation)	Medium
	Mineable ore tonnage (OP)	49. 13 (Direct relation)	Medium
Independent UG mining	Maximum mining depth (UG)	21.33 (Direct relation)	Low
	Mining area border (UG)	65.46 (inverse relation)	High
	Mine life (OP)	76.16 (inverse relation)	Very High
	Production rate and productivity (UG)	21.23 (inverse relation)	Low
	Mineable ore tonnage (UG)	54.16 (inverse relation)	High
	Cutoff grade (UG)	62.41 (Direct relation)	High
Simultaneous OPUG mining with or without a crown pillar	OTD (simultaneous OPUG)	77.45 (inverse relation)	Very High
	Maximum mining depth (simultaneous OPUG)	34.13 (Direct relation)	Medium
	Mining area border (simultaneous OPUG)	16.50 (Direct relation)	Low
	Mine life (simultaneous OPUG)	64.13 (Direct relation)	High
	Mineable ore tonnage (simultaneous OPUG)	18.01 (Direct relation)	Low
	Production rate and productivity (simultaneous OPUG)	15.08 (Direct relation)	Low
Sequential OPUG mining without a crown pillar	OTD (sequential OPUG)	76.35 (inverse relation)	Very High
	Maximum mining depth (sequential OPUG)	48.43 (Direct relation)	Medium
	Mining area border (sequential OPUG)	20.78 (Direct relation)	Low
	Mine life (Sequential OPUG)	64.13 (Direct relation)	High
	Mineable ore tonnage (sequential OPUG)	32.12 (Direct relation)	Medium
	Production rate and productivity (sequential OPUG)	13.23 (Direct relation)	Low
Combinations of simultaneous and sequential OPUG mining without a crown pillar	OTD (simultaneous and sequential)	79.44 (inverse relation)	Very High
	Maximum mining depth (simultaneous and sequential OPUG)	41.12 (Direct relation)	Medium
	Mining area border (simultaneous and sequential OPUG)	21.09 (Direct relation)	Low
	Mine life (simultaneous and sequential OPUG)	71.03 (Direct relation)	High
	Mineable ore tonnage (simultaneous and sequential OPUG)	19.14 (Direct relation)	Low
	Production rate and productivity (simultaneous and sequential OPUG)	17.45 (Direct relation)	Low

* (0-25=Low, 26-50=Medium, 51-75=High and 76-100=very High).

if the reserve is suitable for volume and grade, extraction continues using UG methods.

Previous studies that have been carried out in the field of haulage systems in mines and are the main guide for this research have only focused on the option of open pit mining. In this research, five modes of integrated mining- (a) independent underground mining; (b) independent open-pit mining; (c) simultaneous mining; (d) sequential mining; and (e) combinations of simultaneous and Sequential were evaluated. Also, unlike the previous studies that only evaluated one haulage system, in this research, four modern haulage systems in mines were investigated.

As mentioned earlier, in the cost structure of the mining project, loading and hauling operations contribute the most significant percentage. In the early stages of mining project development, this operation is mainly carried out by the truck and shovel system. In large-scale mining projects (with combined extraction capability) whose lifetimes are measured in decades, an increase in fuel costs, environmental sensitivities, causes an increase in haulage distance, etc. The advantages of the truck and shovel system are significantly undermined as the depth and width of the ultimate pit limits increase. Many instrumental studies have been carried out to evaluate the various effects of mining activity with a semi-quantitative combined approach and multi-criteria decision-making methods. The most critical weakness of these methods is that they are not comprehensive and do not consider the combined extraction mode. In addition, most of these studies have focused on OP mining impacts, and all two OP and UG sections, have been less addressed.

In this study, using a mixed semi-quantitative approach, the effects of haulage systems in large-scale and deep OP mines with combined mining possibilities were evaluated on mining options. According to the evaluations and calculations made regarding the use of haulage systems in OP deep mines with the potential of combined OP and UG mining, it was observed that the use of modern haulage systems leads mining operations in the direction of continuing OP operations. Therefore, it is easy to understand that the potential transition to the UG mining method can be delayed by adopting haulage systems. According to the results of evaluating the use of the modern haulage system in the Sungun copper mine, the most appropriate transportation systems selected were IPCC, TS, BT, and TA, respectively. Also, the use of the modern haulage system in the Sungun copper mine had a direct impact on the following mining options, respectively, with an intensity of -11.03, 32.94, 11.73, 17.06, and 15.07. (a) independent underground mining; (b) independent open-pit mining; (c) simultaneous mining; (d) Sequential mining; and (e) combinations of simultaneous and sequential mining. The obtained results indicate that the use of a modern and suitable haulage system for the mine leads to the desire to continue mining with the OP method, which leads to an increase in OTD. Meanwhile, the modern haulage system has an inverse (negative) effect on the use of independent UG mining, the impact of which is 11.03.

ACKNOWLEDGMENTS

Thanks to all the experts who helped the authors in this research.

Ethical statement

We state that the research was conducted according to ethical standards.

Funding body

This research received no external funding.

Conflict of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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نشریه مهندسی منابع معدنی، سال ۱۴۰۳، دوره نهم، شماره ۲، ص ۳۲-۱۳

نشریه مهندسی منابع معدنی
Journal of Mineral Resources Engineering (JMRE)

دوره نهم، شماره ۲، تابستان ۱٤۰۳، صفحه ۱۳ تا ۳۲
Vol. 9, No. 2, Summer 2024, pp. 13-32

علمی-پژوهشی

ارزیابی اثرات سیستم‌های باربری مدرن بر گزینه‌های معدنکاری

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دریافت: ۱٤۰۲/۰۸/۱۸ پذیرش: ۱٤۰۳/۰۱/۲۵

چکیده

در معادن روباز عمیق با پتانسیل استخراج ترکیبی، بهینه‌سازی سیستم‌های باربری به عنوان فاز فناورانه با بیش‌ترین سهم در کل هزینه‌های بهره‌برداری از جنبه دستیابی به سودآوری پروژه معدن ضروری است. در این مطالعه، با استفاده از یک رویکرد نیمه-کمی- ترکیبی، اثرات سیستم‌های باربری مدرن در معادن روباز در مقیاس بزرگ و عمیق با پتانسیل استخراج ترکیبی بر روی گزینه‌های استخراج بهینه ارزیابی شد. با توجه به نتایج ارزیابی استفاده از سیستم باربری در معدن مس سونگون، مناسب‌ترین سیستم باربری به ترتیب سیستم سنگ‌شکن درون پیت، سیستم شاول- کامیون، کامیون الکتریکی و کامیون با ریل هوایی انتخاب شدند. علاوه بر این استفاده از سیستم باربری مدرن در معدن مس سونگون بر گزینه‌های استخراج زیرزمینی مستقل، روباز مستقل، همزمان، متوالی (غیرهمزمان) و ترکیبی از همزمان و متوالی، به ترتیب شدت تاثیر ۱۱٫۰۳-، ۳۲٫۹۴، ۱۱٫۷۳، ۱۷٫۰۶ و ۱۵٫۰۷ به صورت مستقیم داشت. نتایج به دست آمده حاکی از آن است که استفاده از سیستم باربری مدرن و مناسب برای معدن، تمایل به ادامه استخراج با روش روباز را به دنبال دارد که به افزایش عمق گذار از معدنکاری روباز به زیرزمینی منجر می‌شود.

کلمات کلیدی

استخراج روباز، استخراج زیرزمینی، گزینه‌های معدنکاری، سیستم‌های باربری مدرن.

استناد به این مقاله

بدخشان، ن.، شهریار، ک.، افرائی، س.؛ ۱۴۰۳؛ "**ارزیابی اثرات سیستم‌های باربری مدرن بر گزینه‌های معدنکاری**". نشریه مهندسی منابع معدنی، دوره نهم، شماره ۲، ص ۳۲-۱۳.

DOI: 10.30479/JMRE.2024.19548.1672

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