Original Article

Trends in access and transportation costs in underground mining

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Abstract

Underground mining entails significant investments in accesses, such as ramps and shafts, impacting both initial investment (CAPEX) and operational costs (OPEX). Studies offer models to estimate these costs, considering depth and production rate. Operational transportation costs vary with production and depth, with different studies recommending ramps, shafts, or conveyor belts for economic efficiency. The share of transportation costs in total OPEX is relevant and influenced by the adopted strategy, with models estimating these costs considering depth and required support. In summary, access and transportation costs in underground mining are considerable, with the choice of method influenced by technical and economic factors. This article provides a review and evaluation of implementation and operational transportation costs in underground mines, indicating a trend of lower costs for shaft transportation with mine deepening. The evaluated studies also provide estimates of average costs to assist in initial project estimates.

Keywords: Mine Access; Haulage; Hoisting; Transportation costs; Ramp; Shaft.

1 Introduction

Underground mining necessitates significant investments in access infrastructures, such as ramps and shafts, which impact both initial capital investments (CAPEX) and operational expenses (OPEX). Models for estimating these costs have been proposed [1-3], taking into account depth and mining methods. Transportation operational costs fluctuate based on production rates and depth, with studies recommending ramps, shafts, or conveyor belts depending on economic feasibility [4].

The recent work by Camm e Stebbins [1] highlights cost models for underground mining, including pre-production costs (e.g., access development), with differences in magnitude attributed to exploitation scale and geological/geotechnical conditions. Other cost models include MAFMINE by D'Arrigo [2], OPEX and CAPEX models for underground mines by Araújo et al. [5], and updated MAFMINE models by Araújo [6]. However, these models often lack detailed analysis of transportation access implementation and operational costs, which are crucial factors for selecting mining access methods [7].

More advanced options include the use of simulation tools such as Arena [8] and HaulSim [9], which have been employed for truck transportation analysis, allowing for more dynamic evaluations. However, their application requires more detailed analyses, moving beyond conceptual approaches and rapid comparisons.

2 Methodology

To assess trends in transportation costs — both implementation and operation — a literature review and evaluation of relevant publications were conducted. Table 1 summarizes key studies on cost estimation and their contributions to the selection of exploitation methods. Discretized cost data from works such as Salama [4], Gonen et al. [10], Rupprecht [11] and Elevli et al. [12] were later fitted into equations for better comparison and presentation. These studies present transportation cost options for ramps and shafts at various depths and production rates. For instance, O'Hara and Suboleski [3], focus on shaft transportation, while Camm e Stebbins [1] consider fixed depths with variable production rates.

Curve fitting was conducted using LAB Fit software [13], or two-variable cases and Excel for single-variable cases, selecting equations with the lowest fitting errors.

It is notable that among the studies reviewed, particularly those focused specifically on the selection of mining access methods, the absence of rock mass classification as a criterion for access selection is evident. A contrasting perspective is offered by Paraskevopoulou and Benardos [14], who correlate excavation costs with rock mass classification. However, this absence may be explained by the greater emphasis placed on operational expenditure (OPEX), which naturally excludes the structural execution costs. Additionally, the variability in costs associated with rock mass classification appears to have a negligible impact on the percentage that

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access-related CAPEX represents within the total CAPEX of the mine. As a result, productivity and depth emerge as dominant criteria, as highlighted in the models of Moser [15] and De la Vergne [16].

For the development of this study, the decision was made to normalize the values based on a projected production rate of 1 million tons per year and to analyze cost variations relative to depth. In the initial stage, equations were fitted to the values reported in the reviewed publications. Subsequently, these equations were averaged and normalized to reflect 2019 values, accounting for the period prior to the global health crisis. Only publications providing cost estimates for access development and operational transportation costs were utilized.

3 Results

The adjusted equations for CAPEX and OPEX as functions of depth are presented below.

3.1 Operational Expenditure - OPEX

Most reported OPEX values—except those by Elevli et al. [12]—exhibit good alignment with first-order or exponential equations. Figures 1 to 5 illustrate the fitted equations from various studies. Adjusted equations reflect trends indicating increasing exploitation costs with depth, as expected.

The Producer Price Index [18] was applied for value adjustments, using 2019 as a reference year to avoid economic volatility caused by the COVID-19 pandemic. Table 2 displays the adjusted equations in 2019 US dollars, providing average cost estimates for planning purposes.

Figure 6 presents the graphical representation of the average OPEX for exploitation using Ramp and Shaft. On average, Shaft transportation shows a predominance of lower operational costs. In the mid-range, only at depths up to 250 meters would Ramp transportation be more economical. Although the estimated costs should be interpreted with caution, they support the understanding of the trend toward greater economic efficiency of Ramp exploitation at shallower depths. The caution arises from sample discrepancies, as the costs pertain to different periods, regions, and production scales.

Analyzing the equations individually, it becomes evident that the values with the greatest discrepancies compared to the others are those provided by the equation adjusted to the data from Elevli et al. [12]. This discrepancy can be attributed to (i) technological and productivity advancements since 2002, and (ii) the equation's limited applicability to a depth range of 250-700 meters. Consequently, it can be estimated that Equations 12 and 13, which fits the values in the graph, is valid up to a depth of 700 meters.

For values beyond this range, it is advisable to exclude Equations 14 and 15 from the average cost calculations (Table 3). This adjustment allows for the use of equations that more accurately describe average costs for depths exceeding 700 meters (Figure 7).

Table 1. Articles on cost approaches for access and ore haulage in underground mines

Author	Focus	Key points
[1]	CAPEX and OPEX for conceptual feasibility projects	Estimates CAPEX for Shaft and Ramp as a function of production rate.
[3]	Cost estimates for mining projects.	Presents a simplified model for the cost of executing and equipping underground mine shafts.
[4]	Evaluation of mining haulage alternatives based on NPV and the use of event simulations.	Evaluation of alternatives for different depths (> 1000 m). Shows the relative cost of energy for the different mining options. The conveyor belt is the most economical alternative for mines deeper than 1000 m. The Opex of the disiel truck option is the most sensitive to increases in energy costs and the Shaft option is the lowest.
[10]	Evaluation of ore haulage (Ramp, Shaft or Belt Conveyor) according to OPEX.	Evaluate the alternative based on the production rate and depth of exploration. For production rates of up to 300 ktpa Ramp trucks are the most economical. For high production rates and depths greater than 250 m Shafts are the most economical alternative.
[11]	Evaluation of inflection depth in the choice between Shaft and Ramp for the case of South Africa.	Evaluation of the alternative based on OPEX. Differentiation of costs by truck capacity for Ramps. Higher OPEX for Ramps over 200 m. The inflection point deepens as truck or shaft capacity increases.
[12]	Shaft or Ramp evaluation for an underground chromite mine.	Evaluation of the alternative based on the NPV of the options. Lower CAPEX for Shaft up to depth of 370 m. Higher OPEX for Ramp from 390 m onwards.
[17]	Evaluation based on costs, productivity and execution time. Methodology for choosing access for feasibility studies.	Conveyor belt mining is recommended for production in the range of 7 Mtpa.

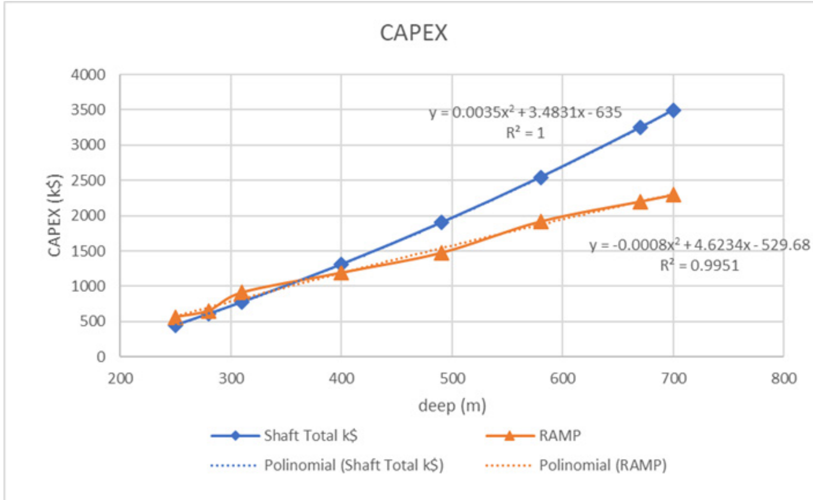

Figure 1. Capex for Ramp and Shaft ajusted for report of Elevli et al. [12].

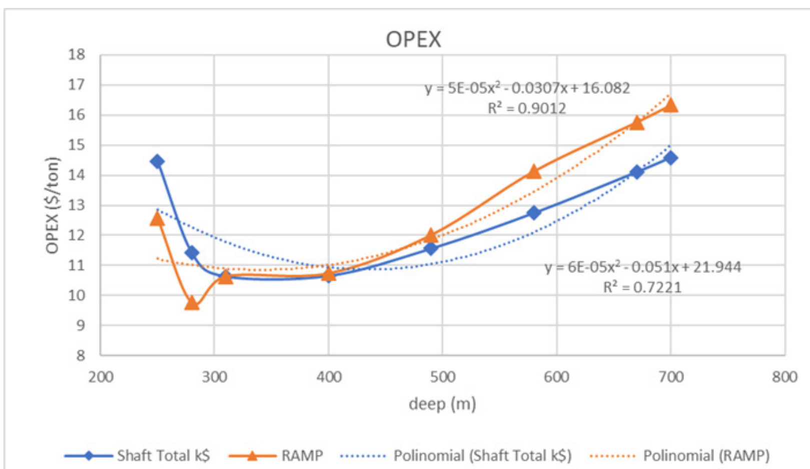

Figure 2. Opex for Shaft and Ramp ajusted for report of Elevli et al. [12].

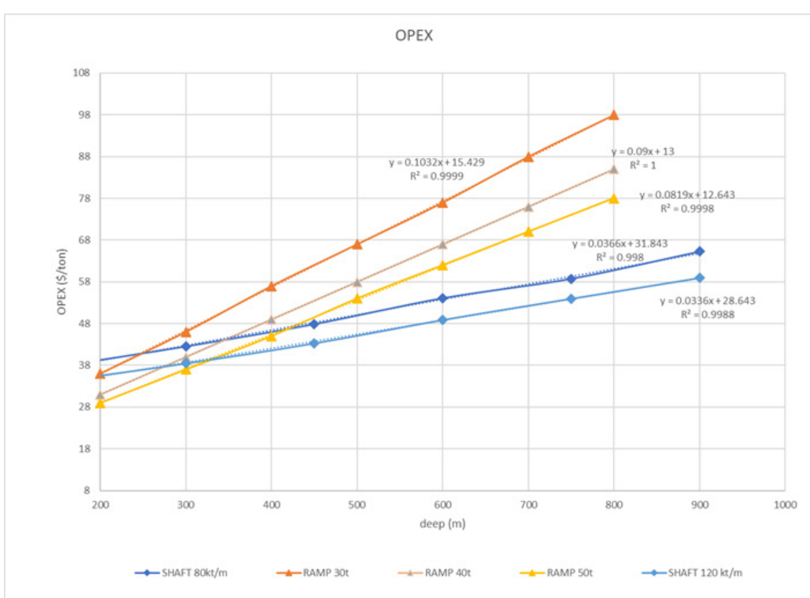

Figure 3. Opex for Ramp and Shaft ajusted for report of Rupprecht [11].

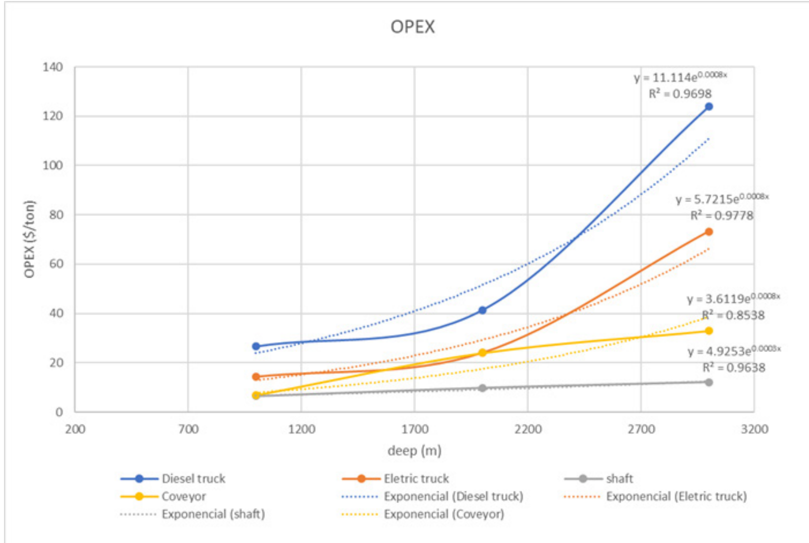

Figure 4. Opex for Ramp and Shaft ajusted for report of Salama [4].

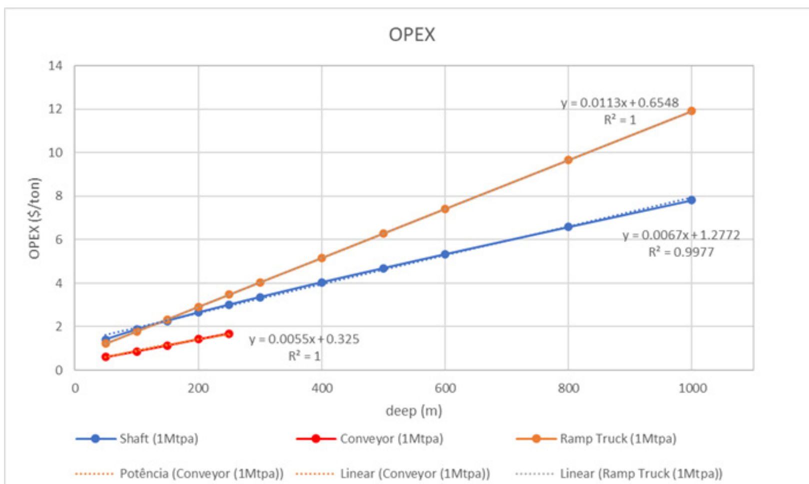

Figure 5. Opex for Ramp, Shaft and Conveyor Belt adjusted for reportof Gonen et al. [10].

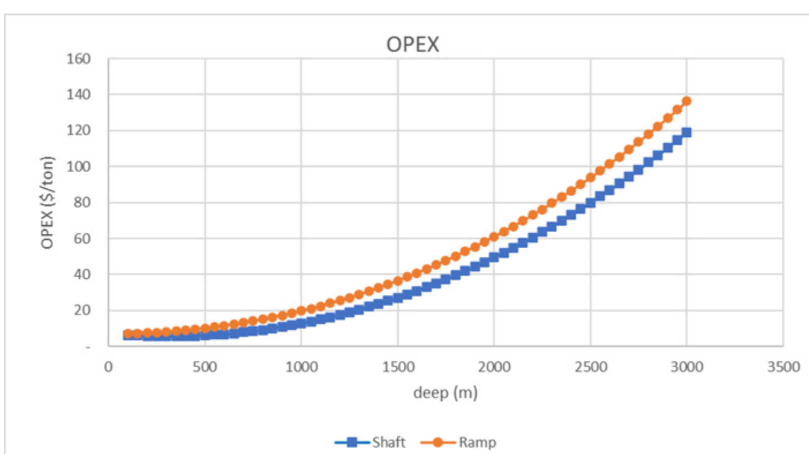

Figure 6. Average Opex for Ramp and Shaft ajusted for reports of Elevli et al. [12], Rupprecht [11], Salama [4], Gonen et al. [10].

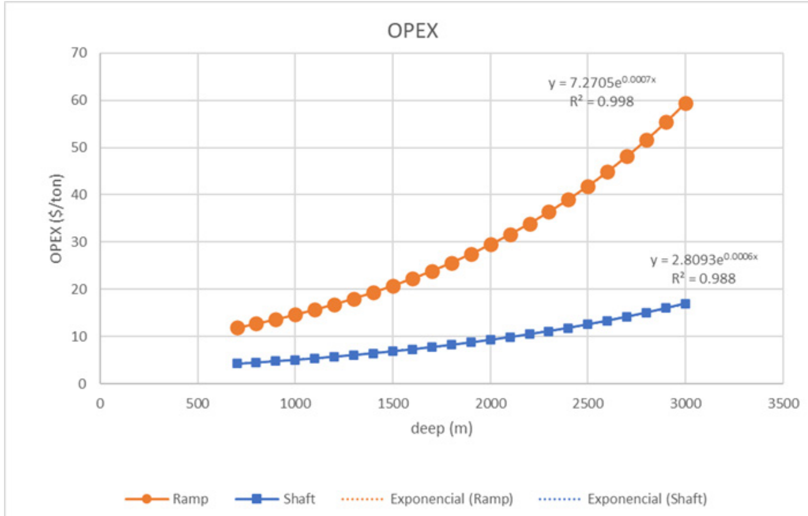

Figure 7. Average Opex for Ramp and Shaft adjusted for reports of Rupprecht [11], Salama [4], Gonen et al. [10].

Table 2. Adjusted equations for exploitation operational costs and general average

Access	Opex ($)		Reference
Ramp	(5*10^-5)*(deep^2)-0.0307*deep+16.082	(1)	[12]
Shaft	(6*10^-5)*(deep^2)-0.051*deep+21.944	(2)	
Ramp	0.1032*deep+15.429	(3)	[11]
Shaft	0.0366*deep+31.843	(4)	
Ramp (Diesel)	11.114*EXP(0.0008*deep)	(5)	[4]
Ramp (eletr.)	5.72151*EXP(0.0008*deep)	(6)	
Shaft	3.6119*EXP(0.0008*deep)	(7)	
Correia	4.9253*EXP(0.0003*deep)	(8)	
Ramp	0.035045*deep^(0.489+2.3867/LN(prod))	(9)	[10]
Shaft	7.34741*(prod/deep)^-0.737199	(10)	
Correia	(58.064+prod)/(0.032059+0.18216*(deep))	(11)	
Ramp	**2E-05*(deep^2) - 0.0051*deep + 8.5249**	(12)	**Adjusted Average**
Shaft	**2E-05*(deep^2 - 0.011*deep + 7.64**	(13)	

Table 3. Operating cost equations for the reports, Rupprecht [11], Salama [4], Gonnen et al. [10]

Access	Opex ($)		Reference
Ramp	7.2705*EXP(0.0007*deep)	(14)	Adjusted Average
Shaft	2.8093*EXP(0.0006*deep)	(15)	

3.2 Contribution of haulage costs to total OPEX

To determine the total operational expenditure (OPEX) of a mining operation, additional costs beyond exploitation must be considered. These include expenses related to development, support, personnel, administration, maintenance, and others. Various authors describe or categorize the components of underground mining costs differently. Generally, however, costs are divided into development, administrative, and operational categories, with the latter typically including exploitation costs. Many economic models, such as those by Camm e Stebbins [19] and Araujo et al. [5], directly estimate the total mining OPEX.

To quantify the contribution of haulage costs to the overall operational expenses, Salama [4] differentiates these costs for various exploitation strategies. This approach allows the measurement of exploitation costs as a proportion of total mining OPEX across different methods (Figure 8). Moreover, it highlights the correlation between total mining costs and energy expenses (Figure 9), facilitating their inclusion in risk analyses or as a critical factor in choosing the most suitable exploitation method.

3.3 Capital Expenditure – CAPEX

When considering the costs of implementing access and exploitation infrastructure, similar limitations to those encountered in operational costs (OPEX) arise, as references to installation costs are scarce. At the conceptual and pre-feasibility levels, these costs are often treated

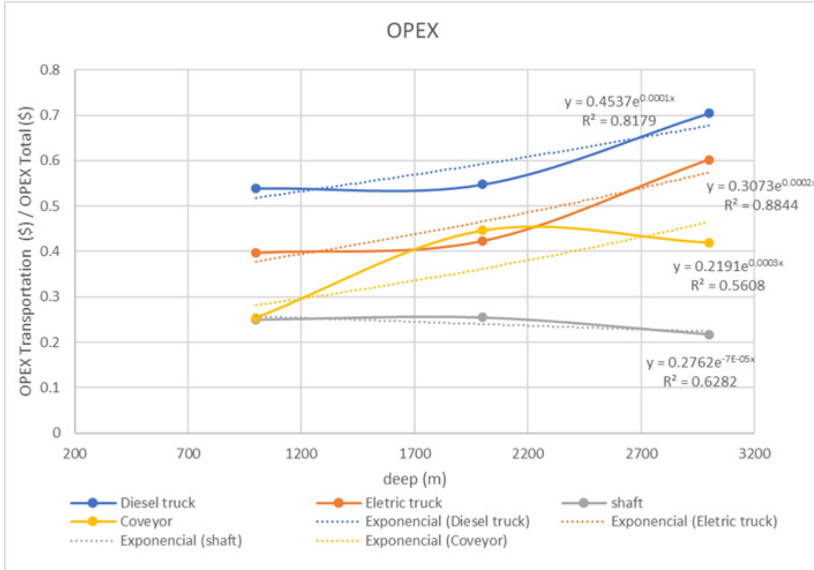

Figure 8. Relationship between transportation Opex and Total Mining Opex for Salama[4] data.

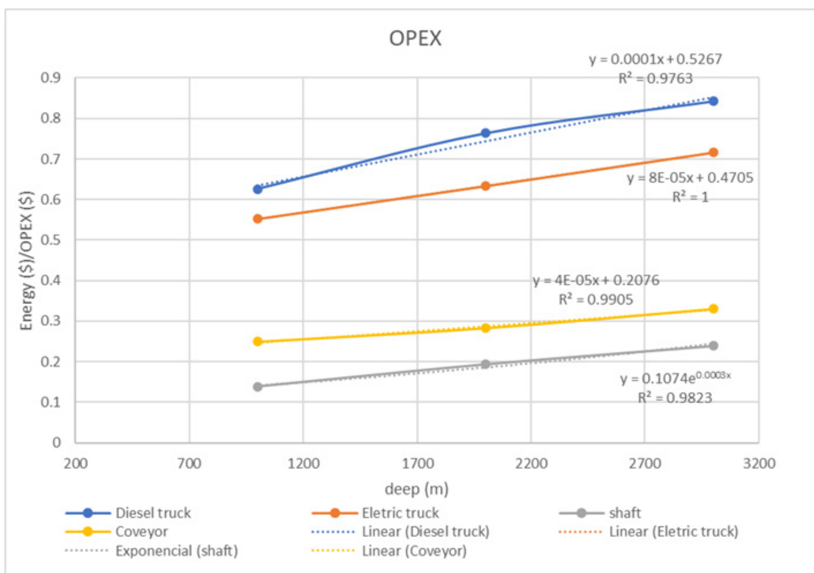

Figure 9. Relationship between Energy cost and transportation Opex for Salama [4].

collectively as the overall mine installation cost, i.e., the total mine CAPEX. Methodologies such as those outlined in Nagle [20], O'Hara and Suboleski [3], and embedded in software like COSTMINE and MAFMINE, provide step-by-step frameworks for estimating implementation costs. These methodologies involve applying specific formulas and parameter selections to derive the final cost estimates. For instance, Elevli et al. [12] offer direct CAPEX estimates, although these estimates share the same limitations observed in OPEX analyses. Camm and Stebbins [19], on the other hand, provide CAPEX estimates for shafts and ramps based on production rates but do not address variations in mine depth.

Another noteworthy cost estimation approach is that of Paraskevopoulou and Benardos [14], which correlates excavation costs with depth and the Geological Strength Index (GSI). Although their estimates focus on tunnels, they can serve as a reference for ramps. It is important to note that other methodologies often do not incorporate geotechnical criteria. Table 4 presents adjusted equations from various references, similar to those shown in Table 2.

However, in the case of tunnels, the big cost difference in terms of geomechanical criteria is when the GSI is below 35 (low quality massif), with the recommendation to use metal crankshafts [21]. For values above 40 (GSI), standard roof bolt supports are typically used, depending on the excavation session.

We can see that the geomechanical criterion plays a relevant role in differentiating costs from lower to upper medium classes, where Class V and IV; have higher costs than Classes IV-I. Another factor to be taken into account is execution time, where Class V and/or when dealing with saprolite (or lower quality soil), execution time can become an obstacle to opting for it in projects, in addition to cost.

Table 4. Adjusted equations for access facility costs

Access	CAPEX		Reference
Shaft	(0.0035*(deep^2)+3.4831*deep-635)*1000	(16)	[12]
Shaft	(((1.85*(prod^0.15))*3.28084)^0.7) *((deep*3.28084)^1.05)	(17)	[3]
Ramp	(-0.0008*(deep^2)+4.6234*deep-529.68)*1000	(18)	[12]
Ramp/Tunel	(deep/0.1)*20148.38*EXP(GSI*(-0.0227))	(19)	[14]

Table 5. Evaluation of the Shaft and Ramp option

	Disadvantages	Advantages
Shaft	Higher installation costs at greater depths and for larger installations.	Lower production costs at greater depths.
		Less sensitivity to energy costs.
	Limited flexibility when installing the structure.	Easier ventilation of the mine.
	High cost of equipping the Shaft system.	
Ramp	Higher production costs at greater depths.	Lower installation costs for greater depths compared to Shaft.
	Greater flexibility - diesel/electrified fleet, fleet increase/reduction.	Greater sensitivity to energy costs.
	More difficult to ventilate (heat and gases) if using a diesel vehicle.	Better ventilation, no gas emissions and less heat generation if the truck is electric.

In the case of the conveyor belt option, it should be noted that the access structure is normally built on an inclined plane and equipped with a belt system. So your CAPEX can be established according to the cost of executing the inclined plane, excluding the cost of equipping the belt.

4 Conclusions

An evaluation of the original publications reveals significant variability in cost estimates, even after monetary standardization. Despite this adjustment, notable discrepancies persist in the fitted equations. Certain trends emerge, with depth consistently identified as a fundamental variable, often surpassing production rates as a cost determinant. While production rates influence costs, their weight in the exploitation OPEX is relatively minor compared to the impact of depth. The data presented by Salama [4] helps elucidate this phenomenon by emphasizing the role of energy costs in exploitation OPEX and, consequently, in total mining OPEX.

Considering the formulations, options such as shafts or ramps with electric fleets may offer greater long-term advantages over diesel ramp fleets, depending on energy availability and volatility. In such cases, access type selection intersects with energy strategies, requiring careful consideration of local energy matrices and future projections. However, other factors must also be evaluated, particularly in choosing between electric and diesel fleets. These include productivity and safety aspects, as highlighted [22].

From a broader perspective, the historical technological evolution in mining suggests that locational and cultural factors also play a critical role in technology selection. For instance, the availability of skilled labor and alignment with local cultural norms can be key factors in a project's success. For equipment automation, beyond energy costs and availability, the presence of qualified maintenance personnel and a robust supply chain must also be assessed.

A less direct but important consideration is community perception of the project. In some cases, choosing an electric (or diesel-free) fleet may serve as a promotional asset for the project. Similarly, selecting a model that supports a local economy accustomed to diesel equipment could positively influence community acceptance. These factors may explain discrepancies between empirical methodologies [13,14] and the actual decisions made in projects.

Therefore, emerging possibilities and trends for more advanced evaluations include decision-making supported by multicriteria analysis [7], combined with risk assessment through scenario simulation — a practice already established in other fields of project development and decision-making. Furthermore, the application of generative machine learning appears as a promising approach, provided that a sufficiently comprehensive database, built from a significant number of cases and projects, is available.

The Table 5 highlights the advantages and disadvantages of different access types based on the referenced studies and the evaluation of equations fitted to the data.

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References

1 Camm TW, Stebbins SA. Simplified cost models for underground mine evaluation: a handbook for quick prefeasibility cost estimates-revised edition. Montana: Mining Engineering Department, Montana Technological University; 2023 [cited 2025 Jan 16]. Available at: https://digitalcommons.mtech.edu/mine_engr/16/

2 D'Arrigo RF. Modelo de estimativa de custos operacionais e de capital em projetos de mineração em fase conceitual baseado no modelo de O'Hara [thesis]. Porto Alegre: Universidade Federal do Rio Grande do Sul; 2012.

3 O'Hara TA, Suboleski SC. Costs and cost estimation. In: Hartman HL, editor. SME mining engineering handbook. Littleton: Colo; 1992. p. 405-24.

4 Salama A. Haulage system optimization for underground mines a discrete event simulation and mixed integer programming approach [thesis]. Lule: Lule University of Technology; 2014.

5 Araújo VIAB, Petter CO, Cardozo FAC, Petter RA. Modelo de estimativa dos custos de capital e operacional de lavra subterrânea através de curvas parametrizas obtidas por estudos de viabilidade. In: Anais X CBMINA. Belo Horizonte: IBRAM; 2021 [cited 2025 Jan 16]. Available at: https://ibram.org.br/wp-content/uploads/2021/04/T-67-Vinicius-Igor-Albuquerque-Batista-de-Araujo.pdf

6 Araújo VIAB. Aderência das estimativas dos custos de capital e operacional do MAFMINE e das equações de Camm e Stebbins em projetos de lavra subterrânea [Master Thesis]. Porto Alegre: Universidade Federal do Rio Grande do Sul; 2023.

7. Cardozo FAC, Petter CO, Petter RA. Multicriteria Analysis and ESG Approach in the Choice of Underground Mine Access. In: ABM Proceedings. São Paulo: Editora Blucher.; 2023 [cited 2025 Jan 16]. Available at: http://abmproceedings.com.br/ptbr/article/anlise-multicritrio-e-abordagem-esg-na-escolha-de-acesso-de-mina-subterrnea.

8 Hashemi AS, Sattarvand J. Application of ARENA simulation software for evaluation of open pit mining transportation systems: a case study. In: Niemann-Delius C, editor. Proceedings of the 12th International Symposium Continuous Surface Mining. Cham: Springer International Publishing; 2015 [cited 2025 Jan 16]. p. 213-24. Available at: https://link.springer.com/10.1007/978-3-319-12301-1_20

9 Karikari YS, Askari-Nasab H. A Comprehensive Simulation Model for Mining Operations: Development, Implementation, and Validation Using HaulSim. In: Badiozamani, MM, Pourrahimian, Y, Ben-Awuah, E, Moradi Afrapoli, A and AskariNasab, H, editors Mining Optimization Laboratory (MOL) – Report Twelve. Edmonton, Canada: University of Alberta; 2024. p. 407-427.

10 Gonen A, Malli T, Kose H. Selection of ore transport system for a metalliferous underground mine / Dobór systemu transportu rud w kopalni podziemnej rud metalu. Archives of Mining Sciences. 2012;57(3):779-785.

11 Rupprecht S. Mine development - Access to deposit. Johannesburg: The Southern African Institute of Mining and Metallurgy. 2012.

12 Elevli B, Demerci A, Dayi O. Underground haulage selection: shaft or ramp for a small-scale underground mine. Journal of the Southern African Institute of Mining and Metallurgy. 2002;102(5):255-260.

13 Silva CMDPS, Cavalcanti CGB, Silva DDPS, Soares IB, Oliveira JAS, et al. LAB Fit ajuste de curvas: um software em português para tratamento de dados experimentais. Revista Brasileira de Ensino de Física. 2004;26(4):419-427.

14 Paraskevopoulou C, Benardos A. Assessing the construction cost of Greek transportation tunnel projects. Tunnelling and Underground Space Technology. 2013;38:497-505.

15 Moser P. Primary development of underground hard rock mines. In: Ayres da Silva, LA; Chaves, AP, editors. In: Symposium on Mine Planning and Equipment Selection. Rotterdam: A.A. Balkema; 1996. p. 31-3.

16 De la Vergne J. Hard rock miner's handbook. Edmonton: Stantec Consulting; 2008.

17 Gromov EV, Belogorodtsev OV. Improvement of access methods for ore reserves beyond ultimate limits of open pits. Eurasian Mining. 2019;(1):16-20.

18 Ong LL. Burgernomics: the economics of the Big Mac standard. Journal of International Money and Finance. 1997;16(6):865-878.

19. Camm TW, Stebbins SA. Simplified Cost Models for Underground Mine Evaluation: A Handbook for Quick Prefeasibility Cost Estimates. Butte: Montana Technological University; 2020.

20 Nagle AJ. Aide a l'estimation des parametres economiques d'un projet minier dans les etudes de prefaisabilite [thesis.]. Paris: ENMP; 1988

21 Petroutsatou C, Lambropoulos S, Pantouvakis JP. Road tunnel early cost estimates using multiple regression analysis. Oper Res Int J. 2006;6(3):311-322.

22 Jacobs W, Hodkiewicz MR, Braunl T. A cost–benefit analysis of electric loaders to reduce diesel emissions in underground hard rock mines. IEEE Transactions on Industry Applications. 2015;51(3):2565-2573.

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