Choice of access for underground mining for feasibility studies

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Abstract

This study presents a review of the methodology for choosing the type of access and exploitation methodology for underground mines, being the choice of the type of access, one of the initial stages of the conceptual projects. To this end, in addition to literature verification, technical feasibility reports of recent projects were analyzed, made available by mining companies listed on the Toronto Stock Exchange. In this report, data were extracted referring to technical and productive characteristics of the projects, thus allowing comparison with classic methodologies for the choice of types of access and the compilation of a new flowchart, adhered to the current mining industry. The data from the projects were separated considering the mining methods with the largest number of samples, as well as the productive and mineral deposit characteristics. As a result, a chart is presented for the choice of access and mining method as a function of productive characteristics, ore body geometry and rock mass quality. Updating the limits considered for depth and daily production corresponded to a significant improvement in the response of the suggested access type and made it compatible with that presented in the feasibility projects.

keywords: mining infrastructure, underground mine access, mine access choice, mine exploitation.

1. Introduction

The study of technical and economic feasibility is considered the basis for the implementation of projects of any nature. In the mining sector, where typically one works with projects valuing millions of dollars, due to large-scale operations, and where even the expansion of prospective studies - drilling and laboratory tests, means great expenditures, the preliminary estimates and respective choices of layout of the enterprise become of paramount importance. In underground mining we still have, if compared to open pit, an extra number of variables to choose from, such as the mining method, geometries, and associated infrastructure, which includes the type of access and exploitation method. Although these are factors of great influence, in predictability models such as O'hara (1980), they are choices of the designer.

For quick estimates (called "quick evaluations") the mining sector uses estimation by similarity of values and parameters with projects already executed or with cost estimates executed in detail (detail projects) as presented by Carriconde (2010). La Vergne (2003) also discusses such practices in mining. More recently Camm and Stebbins (2020) present methodology and parameters for estimating costs for underground mining, where one can observe the impact of the cost of the type of access to be chosen in the form of costs, as do Elevi *et al.* (2002). The need for proper choice of access for underground mining and how it impacts a project is discussed by Rupprecht (2012), Gomes (2015), Wilson *et al.* (2004), Tatiya (2005), Elevi *et al.* (2002), Costa (2015) and Costa *et al.* (2017). The appropriate choice of the type of access and/or method of ore extraction is a key criterion for mining projects, which can make a project unfeasible, either prematurely or later.

Another relevant aspect for the choice of accesses and little addressed in preliminary estimates is the influence of rock mass quality, which as Paraskevopoulou and Benardos (2013) present, is a key factor in the cost of underground excavations. We thus see a lack in the approach of the access and exploitation method in cost estimates and conceptual modeling of underground mining projects, according to the methodologies presented by O'hara (1980), Nagle, (1990) and

D'Arrigo (2012), where the choice of the type of access and exploitation method lacks a methodology of choice.

Thus this article proposes to address the relationship between underground mining methods, ore production, geometry of the ore body of the stope and type of access, based on feasibility studies of underground mining projects, obtained from the System for Electronic Document Analysis and Retrieval (SEDAR) of the Canadian Securities Administrators (CSA), so as to evaluate the possibility of improving access selection methodologies for the early phases of underground mine projects. So in the future it can incorporate a choice access model for underground mining into the MAFMINE model, structured by D'Arrigo (2012) under the Models developed by O'Hara (1980). Thus, increasing the adherence of the outputs.

MAFMINE is an educational tool developed by UFRGS (https://www.mafmine.com.br/v3/) based on parametric models to estimate investment and operational costs in mining. The software itself, in its 3.0 version, is based on the use of a computer model known as client-server. Access choice is the main contribution of the research presented in this article, to be implemented in the 3.1 MAFMINE new version.

2. Feasibility Studies

According to Bullock (2011), the preparation of technical feasibility reports, with reliable and auditable data, aims to demonstrate that the mining project is feasible, that it can be sold to another party, or that it can be put into maintenance waiting for a possible new technology for its economic utilization or for a market opportunity. The descriptions of the three phases of economic and or financial feasibility of a mining venture, according to Lee (1984), are placed in the following order: (i) Conceptual Study: Represents the transformation of an idea or concept to a business opportunity to be presented to possible investors, where costs and methods are obtained through historical data; (ii) Preliminary or pre-feasibility study: From the approval of the conceptual study, the next phase consists of determining which parts of the previous technical report need further detailing, which parts of the project are critical to the point of making the project unfeasible and which item needs an in-depth study. All these questions are asked in the feasibility study; (iii) Feasibility study: This is the defined study that encompasses the technical, environmental and commercial aspects of the project in order for a decision to be made, whether or not to approve it, considering all the risks and opportunities raised in the previous studies.

In accordance with NI code 43-101, whose purpose is to ensure that misleading, erroneous or fraudulent information relating to mineral properties is not published and promoted to investors on stock exchanges supervised by the CSA; all technical studies must contain the following order:

(i) Summary; (ii) Introduction; (iii) Qualified Person (QP); (iv) Property description and Location; (v) Accessibility, climate, infrastructure and surface relief; (vi) Local history; (vii) Geology and mineralization; (viii) Deposit type; (ix) Geological exploration; (x) Drilling, sampling, analysis and quality controls; (xi) Technological characterization of minerals; (xii) Mineral resource estimate; (xiii) Mineral reserve estimate; (xv) Beneficiation methods; (xvi) Infrastructure; (xvii) Environmental and social impact studies; (xviii) Market study; (xix) Operating costs and venture capital; (xx) Economic analysis; (xxi) Conclusions; and (xxii) References.

3. Underground accesses

Regardless of the mining method to be adopted (in underground mining), as seen earlier, the development of access and basic infrastructure associated with these are precursor stages of mining, because it is the initial step to any operation of underground mining access to the ore body, associated with the need for development of basic structures to operate in appropriate conditions and with observance of safety and environmental criteria, such as a ventilation system, emergency exits, support of the excavation, among other structures, which for many enterprises, constitute basic infrastructure to the development of the operation. Naturally, if in the open pit, we have direct access to the ore or the removal of sterile over it (cover), in underground mining, there is the need for access through structures such as shafts, ramps, inclined drifts and / or tunnels (Figure 1), which have the function of transposing strata without interest as to exploitation. Thus, in a simple way, the importance of proper planning of the infrastructure and access to be performed is verified. Along these lines, Costa (2015) discusses these structures, highlighting the need for the correct selection of which parameters to use, as an optimized factor in exploration. Being compiled from Costa (2015):

- Shaft: Vertical (or subvertical) excavation, normally circular, tends to become the most viable option with the increase in the depth of mining for the flow of production, people, and equipment. For this purpose, it is equipped with an elevator system.

- Inclined drifts: Rectilinear excavation with plunge towards the ore body. It is a viable option for bodies that are not too deep and with production compatible with transportation by trucks or conveyor belts (case of coal), being the recommended option for the use of the latter. Depending on the depth to be reached and the inclination, it may have its entrance at a considerable horizontal distance from the ore body. It presents as an advantage, compared to helical ramps, the option of installing winches and train systems.

- Ramp: Excavation towards the ore body in a "zigzag" or spiral pattern. Performed in such a way so as to avoid locational problems, such as sloping plane, transportation of ore by trucks, etc.

- Tunnel: Horizontal or sub-horizontal excavations, in the case of access to mineral bodies through slopes or underground routes. They connect chambers, stopes, infrastructure structures, and underground mines, which you may wish to interconnect. In diffuse ore bodies, it is common to choose to explore specific portions of the body, not necessarily adjacent, with the objective of greater economic exploitation. Naturally, underground galleries must be used to connect the portions to be explored; dynamics typically seen in the sublevel stope method.

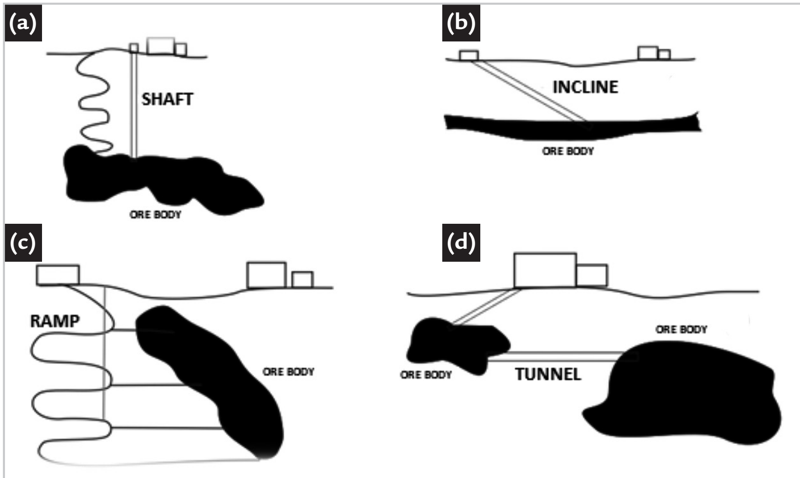

Figure 1 - Main accesses for underground mining.

La Vergne (2003) addresses the differences between the forms of access and exploitation method, considering that for ramps, there is the option of exploitation by trucks or conveyor belt, pointing to a greater production flexibility for the options with ramp and trucks. However, simulations by Haviland and Marshall (2015) point to a limitation in the flexibility of ramps, given that due to the geometry, there is an optimal truck capacity. Salama (2014) on the other hand, while highlighting the flexibility of using diesel trucks, considers the limitations imposed by heat and gas generation. This may be a limiting factor for the number and power of equipment, not the dimensions of the access.

3.1 Access choice

The choice for the type of underground access, which includes access for equipment, personnel, supplies and production flow, tends to take into consideration economic factors. Several authors have discussed the subject, such as McCarthy and Livingstone (1993), who present comparisons between shaft and inclined plane as to the cost of execution and production flow. However, usually the initial choice tends to be based on success stories or on so-called 'rules of thumb', which are also structured on success stories, such as those put together by La Vergne (2003).

Another alternative for the choice of access and transport is the use of algorithms or logical flowcharts (Figure 2) as proposed by La Vergne (2003) and Moser (1996), where considering the case of 50 underground mines (at the time), presents the following algorithm for determining the type of access to be operated, considering input parameters such as depth, production, and rock mass quality. Such an algorithm, due to its good applicability, is widely used for conceptual studies in mining until the present time, although it is temporarily outdated, considering the technological evolution.

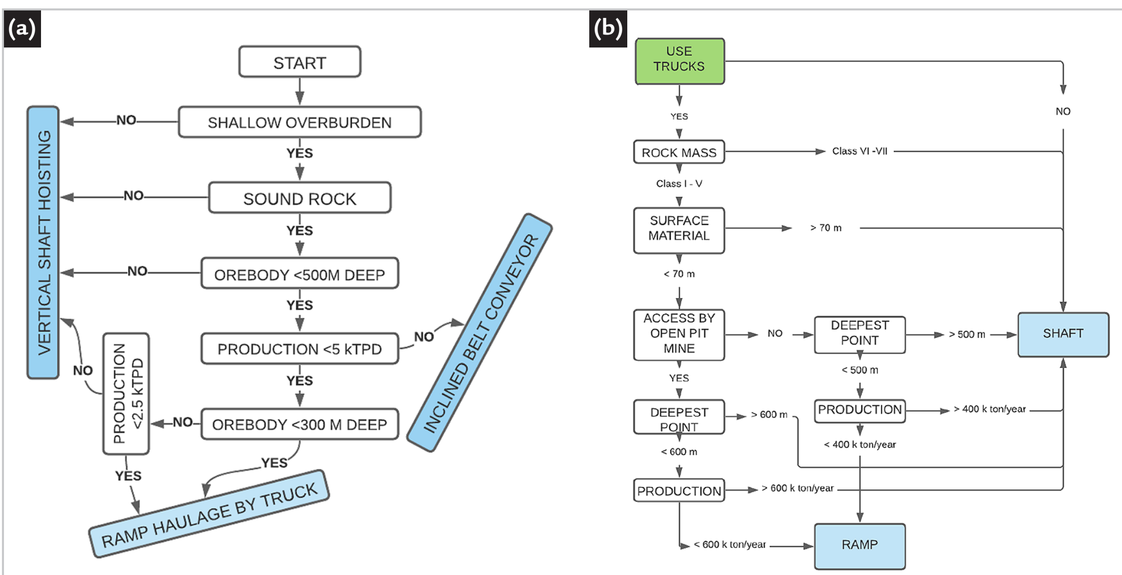

Figure 2 - Algorithm for determining the type of Underground Mining Access presented by (a) La Vergne (2003) and (b) Moser (1996).

However, one should note options not addressed by the author, such as the use of conveyor belt systems and equipment evolution, which allows the use of trucks with high productivity, enabling their use in deeper deposits. We can also take into consideration, as Rupprecht (2012) addresses, the energy cost that can make the use of shafts uneconomical, depending on the depth and tonnage exploited. Thus, the methodologies proposed by Moser (1996) and compiled by La Vergne, 2003, become outdated, besides being dependent on the previous choice of the exploration method. Elevi *et al.* (2002), point out how variations in costs with electricity, fuel and evolution cause distortions in the choice of access and exploitation. Costa *et al.* (2017), point out that the boundary choice between ramp and shaft trucks has gone from the proposed 350 m to about 1000 m. Another example of disruption is the case of Sweden, where Salama (2014) points out that the automation and use of electric equipment becomes economically advantageous compared to diesel.

4. Methodology

To understand the economic feasibility studies, we evaluated parameters and estimated costs of underground mining projects, whose data are available for consultation on SEDAR. These projects have a wide range of locations (countries), body geometry, mining methods, and consequently production and development rates. To format the database, 435 projects published between January 2012 and July 2020 regarding underground mining were analyzed, and of these, 59 effectively contributed information to structure the database for evaluation, which are feasibility studies.

The database includes the following information:

(i) Locality, (ii) Year, (iii) Ore, (iv) Mining Method, (v) Project Phase, (vi) Geometry, (vii) Production, (viii) Geomechanical Classification, (ix) CAPEX, (x) OPEX;

Statistical analysis and equation fitting tools were used to identify key parameters in productivity, costs and the capital investment to produce one ton of ore per day, called unit intensity (UI). To validate the models, the adherence of the data to the generated model and points taken from the database and articles on the subject were evaluated. With the structured database, an adherence check was performed for the methodologies presented by Moser (1996) and La Vergne (2003). Following the same models and the limits proposed in the works of Elevi *et al.* (2002), Rupprecht (2012), Gonen, Malli and Kose (2012); a flow chart was adapted and verification was made for the choice of accesses based on the project reports consulted and key limits presented by Moser (1996) and La Vergne (2003).

4.1 Database

Of the projects analyzed, 59 were used. Figure 3 and Figure 4 show the characteristics of these projects. The reasons for the discarded studies were due to mining methods that are not contemplated in the MAFMINE, such as Block Caving, *in situ* mining among others, and studies where it is not possible to identify the operational cost per mining method. Most studies are located in North America (Canada, USA and Mexico) and Africa, according to Figure 3.

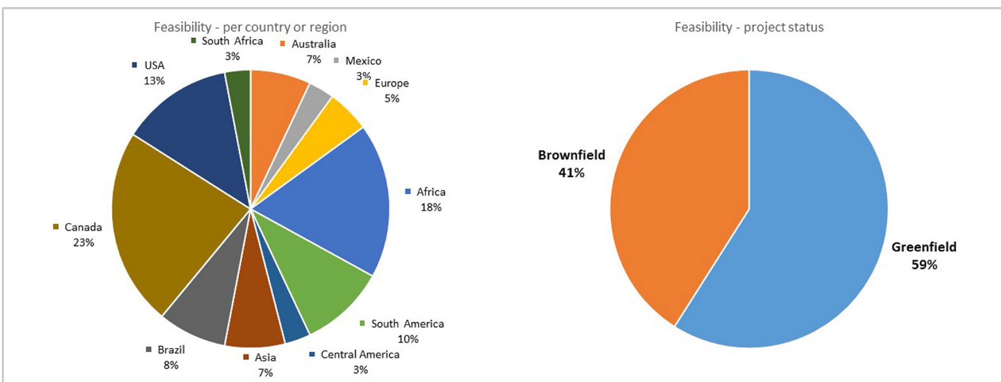

Figure 3 - Distribution of projects by country and project status.

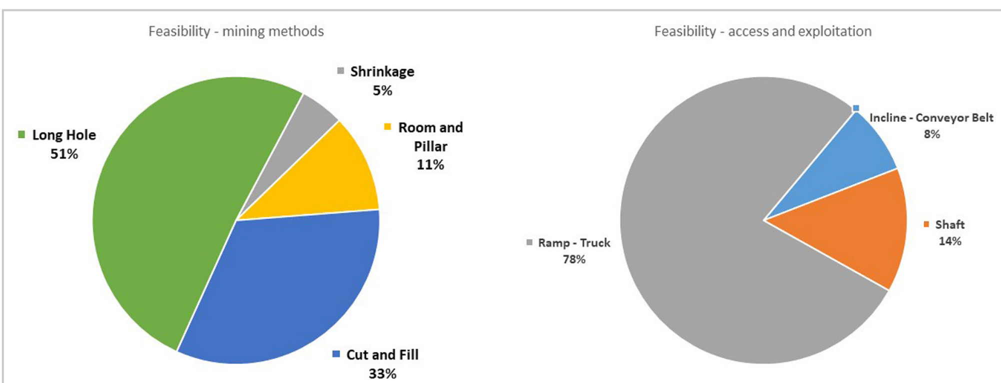

Figure 4 - Distribution by mining and transport method.

And of the methods of transporting the ore to the surface and its respective access, most projects have adopted the use of ramp trucks, followed by Shaft and belt conveyors through shafts and inclined planes.

5. Results and discussion

Considering as base the model compiled by La Vergne (2003), algorithm of Figure 2, the limits of production and depth of the ore body were considered and re-evaluated as determinant factors for the choice of access. For re-evaluation of the limits as presented in Figure 5, works presented by Elevi *et al.* (2002), Rupprecht (2012), Costa *et al.* (2017); were considered. Terms, such as sound rock, were replaced with the aim of reducing subjectivity and enabling the use of geomechanical classifications. Figure 5 presents the proposed update to the flowchart.

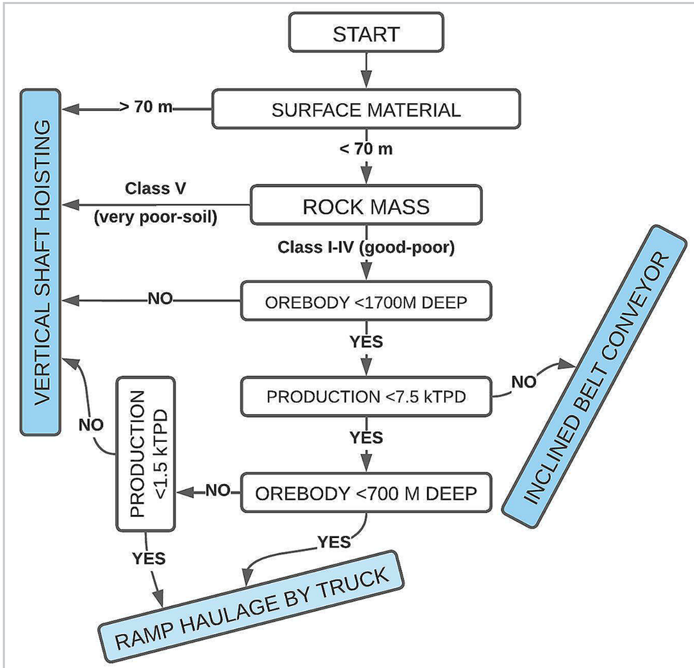

Figure 5 - Algorithm for determining the type of Access to Underground Mining.

For re-evaluation of the algorithm limits, referring to daily production and depths, the data from SEDAR forecast reports were considered, evaluating the best adherence of the algorithm response to the choice adopted in the projects. On the other hand, the limit criterion for unconsolidated material (surface material) was given due consideration, due to the difficulty resulting from the large time and cost to develop the ramp in unconsolidated material. Taking into account that the advancement in unconsolidated material is slow and costly, a depth of 70 meters was estimated as the feasible limit. Table 1 presents the compilation of the main changes considered in the flowchart and the motivations.

Table 1 - Considerations about the algorithm's key parameters.

Key parameter	Reference	Update	Comment
Surface material	Criterion already adopted by Moser (1996).	70 m as limit for Ramp/Incline	Greater depths represent cost and development time overruns. Considering high costs for stripping and required supports. Development time would exceed 1 year.
Rock Mass	Use of Rock Classes presented by Moser (1996). Qualitative evaluation by La Vergne (2003). According to SEDAR reports	Class I- IV as limit for Ramp/Incline	The evaluation of the SEDAR reports points to such classes with ramp/decline uses, not reposting Class V uses. Choice of Class allows automation of the algorithm without subjectivity.
Deep	Update of the limit presented by La Vergne (2003) and Moser (1996)	Deep < 1700m as limit for Ramp/Incline	The SEDAR database shows projects with depths greater than 1000 m with the option to ramp, and there has been an occurrence of projects with depths greater than 1600 m. The limit of 1700 now encompasses the reported cases, representing the worst case, and is in line with reported trends on fleet automation and electrification.
Production	Update of the limit presented by La Vergne (2003) and adjustment with SEDAR reports	Production > 7.5 kTPD as rule for belt conveyor	Updating the limit based on SEDAR reports to include projects with a conveyor belt option.

Compared to the feasibility projects analyzed, the proposed model presented an adherence of 71% to the access and exploration methods adopted. When comparing the mines and access choices listed by Costa *et al.* (2017), whose projects have already been implemented, we see a higher adherence of 65 %. In contrast, using the original algorithm of La Vergne (2003), we have a marked improvement in adherence, being that for the same database presented 39%.

Figure 6 presents the relationship between depth and daily production for the feasibility projects reported on SEDAR and the operating mines presented by Costa *et al.* (2017). The graph highlights the type of access and the limits established according to Figure 5 and Table 1.

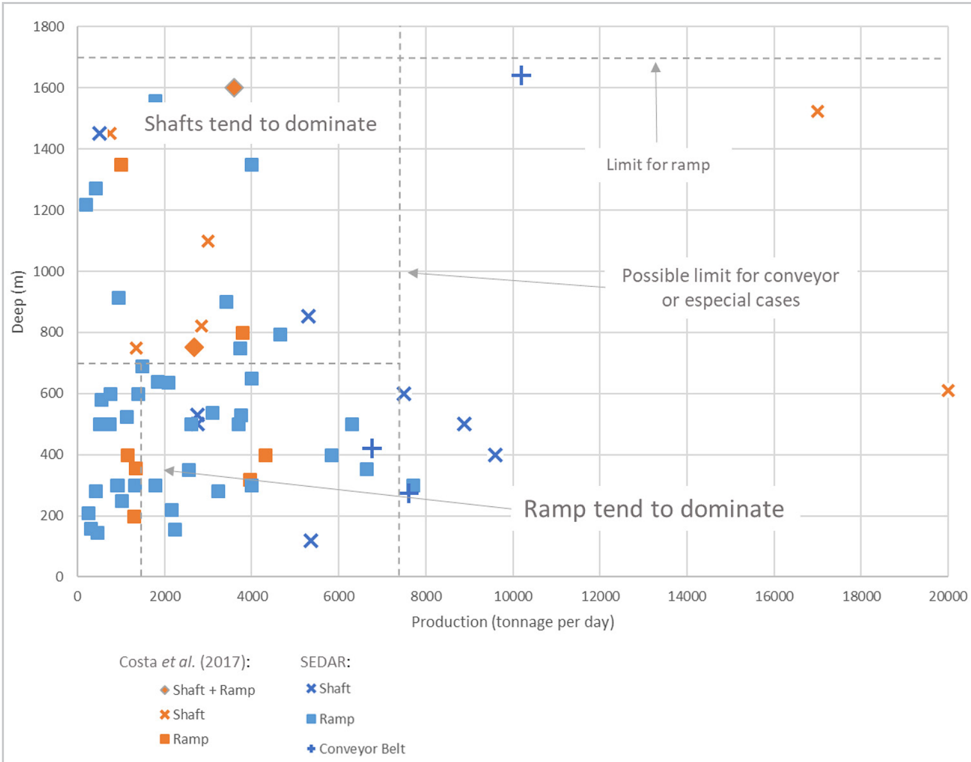

Figure 6 - Relationship between depth, production, and type of access chosen.

The graph shows a tendency for recent projects to adopt the truck ramp system, and that the limits of production and depths defined for the algorithm update are adequate for the distribution of cases. The limits of depth of 700 m and production of up to 1.5 ktpd showed to be a conservative framework to indicate the option for ramp and trucks. Dashed lines in the graph represent the algorithm's production and depth adjusted limits. It should be noted that the limits were adjusted according to the SEDAR reports, and that lesser-used mining methods such as block caving, or special cases are beyond the adherence of the adjusted algorithm. However, even for mines in operation, as can be seen in Figure 6, the key limits show good adherence.

6. Conclusion

The present study demonstrates the relationship between deposit geometry, production rates and the choice of access and exploration method. Based on the mining project reports, it is observed that in a broad sense, the access methodology presented good adherence, having been compatible with the choices adopted in 70 % of the evaluated data. Considering the proposed limit updates for depths and daily production.

Based on this study, and by the database survey, a new flowchart will be inserted for access choice in the MAFMINE software (available at <http://www.mafmine.com.br/v3/#>), in progress at the Mineral Processing Laboratory (LAPROM), at the Federal University of Rio Grande do Sul (UFRGS), to improve the adherence of the equations of operational cost, capital and among others of the software.

It is important to highlight how the reevaluation of access methodology is something periodic and changeable, given the insertion of new technologies, productivity gains, and variations in input costs. From the works of Elevi *et al.* (2002), Rupprecht (2012), and Wilson *et al.* (2004), such influences are evident. Merchier *et al.* (2015) add how developments in productivity and new technologies may change future scenarios, such as the introduction of high productivity locomotive and belt systems, which can be applied to hard rock mining, which used to be mostly explored by trucks or shafts. Thus, it is essential for the success of a project to look at the current state of the art, to validate the choice for the type of access and exploitation method.

Regarding the geotechnical aspect, the mechanical quality of the ore and its bedrock, a criterion always raised as relevant, we see a lower relevance in practice, when looking at feasibility projects. Few of the evaluated projects actually score the geotechnical criterion, let alone place it as a limiting factor in the choice of accesses. However, the use of geomechanical classification as a variable in the choice of access makes the weighting of rock quality less subjective in comparison to the previously proposed choice methodologies.

References

BULLOCK, Richard L. Mineral property feasibility studies *In*: DARLING, P. ***SME - Mining Engineering Handbook***. [*S.l.*]: [*s.n.*], 2011. p. 227-261.

CAMM, Thomas W.; STEBBINS, Scott A. ***Simplified cost models for underground mine evaluation***: a handbook for quick prefeasibility cost estimates. 2020.

CARRICONDE, Milton Correa. ***Verificação da aplicabilidade do programa MAFMO como ferramenta auxiliar na estimativa de custos em projetos conceituais.*** 2010. Dissertação (Mestrado) - Programa de Pós Graduação em Engenharia de Minas, Materiais e Metalúrgica. Escola de Engenharia da Universidade Federal do Rio Grande do Sul, Porto Alegre, 2010.

COSTA, Leandro de Vilhena; SILVA, José Margarida da; LIMA, Hernani Mota de. Analysis of options of production and access ways in underground mines. ***REM - International Engineering Journal,*** v. 70, n. 2, p. 237-242, 2017.

COSTA, Leandro de Vilhena. ***Análise das opções de vias de produção e acesso em minas subterrâneas.*** 2015. Dissertação (Mestrado em Engenharia Mineral) - Universidade Federal de Ouro Preto. Ouro Preto. MG. 2015.

D'ARRIGO, R. A. ***Modelo de estimativa de custos operacionais e de capital em projetos de mineração em fase conceitual baseado no modelo de O'Hara***. 2012. Dissertação (Mestrado) - Programa de Pós Graduação em Engenharia de Minas, Materiais e Metalúrgica. Escola de Engenharia da Universidade Federal do Rio Grande do Sul, Porto Alegre, 2012.

ELEVI, B.; DEMIRCI, 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,*** v. 102, n. 5, p. 255-260, 2002.

GOMES, David André Prata. ***Gestão de riscos na construção de túneis e obras subterrâneas.*** 2012 Dissertação (Mestrado em Engenharia Civil) - Instituto Superior de Engenharia de Lisboa. Lisboa. 2012.

GONEN, Alper; MALLI, Tahir; KOSE, Halil. Selection of ore transport system for a metalliferous underground mine/Dobór systemu transportu rud w kopalni podziemnej rud metalu. ***Archives of Mining Sciences,*** 2012.

HAVILAND, David; MARSHALL, Joshua. Fundamental behaviours of production traffic in underground mine haulage ramps. ***International Journal of Mining Science and Technology,*** v. 25, n. 1, p. 7-14, 2015.

LA VERGNE, Jack. ***Hard rock miner's handbook.*** Tempe/North Bay: McIntosh engineering. ISBN 0-968006-1-6, 2003.

LEE, T. D. Planning and mine feasibility study – an owner perspective. *In*: NWMA SHORT COURSE "MINE FEASIBILITY - CONCEPT TO COMPLETION.". 1984. Spokane. ***Proceedings* [...]**. Spokane: Northwest Mining Association, 1984.

MCCARTHY, P. L.; LIVINGSTONE, R. Shaft or decline? – an economic comparison. Open pit to underground: making the transition. ***AIG Bulletin,*** n. 14, p. 45-56, 1993.

MERCHIERS, Andreas; BRUDEK, Gregor; DAMMERS, Markus. Advantages and applications of rail haulage systems in underground hard rock mining operations. **Mining Report,** v. 151, p. 400-416, 2015.

MOSER, P. Primary development of underground hard rock mines. *In*: SYMPOSIUM ON MINE PLANNING AND EQUIPMENT SELECTION. 1996. São Paulo. ***Proceedings [...]***. São Paulo, 1996. p. 31-3.

NAGLE, A. J. Aide a l'estimation des paramètres economiques d'un projet minier dans les etudes de prefaisabilité. [*S.l.*]: [*s.n.*], 1988.

O'HARA, T. Alan. ***Quick guides to the evaluation of orebodies.*** publisher not identified, 1980.

PARASKEVOPOULOU, Chrysothemis; BENARDOS, Andreas. Assessing the construction cost of greek transportation tunnel projects. ***Tunnelling and underground space technology,*** v. 38, p. 497-505, 2013.

RUPPRECHT, S. M. ***Mine development–access to deposit.*** University of Johannesburg, p. 101-121, 2012.

SALAMA, Abubakary. ***Haulage system optimization for underground mines.*** 2014. PhD thesis, Luleå Tekniska Universitet. 2014.

TATIYA, Ratan Raj. ***Surface and underground excavations***: methods, techniques and equipment. CRC Press, 2005.

WILSON, R. B.; WILLIS, R. P. H.; DU PLESSIS, A. G. Considerations in the choice of primary access and transportation options in platinum mines. *In*: INTERNATIONAL PLATINUM CONFERENCE 'PLATINUM ADDING VALUE, 1, 2004, Sun City, South Africa. ***Proceedings* [...]**. 2004. p. 3-7.

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