Original Article

Methodology to include the comminution specific energy into open-pit strategy mine planning using global optimization

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Abstract

Strategic Mine Planning demands an accurate knowledge of the mineral deposit, being very important the use of block models supported by Geometallurgy. Currently, the methodology used considers the mine planning divided into parts (ultimate open pit, pushbacks, scheduling). Global optimization can guarantee the optimal solution once all steps are solved together. In the present study the database Marvin was used and the geometallurgical variable comminution specific energy was included. In the first scenario, called GeoMet1, a *ramp-up* was included in the first three years. In the GeoMet2, different maximum movement ranges were defined, as well as the implementation of ore stockpiles and their subsequent rehandling. Gains of 9.66% in NPV and 5.18% in ore production were found for GeoMet2. The second scenario presented ore production adhering to the programmed, in addition to greater stability in the stripping ratio. In addition, GeoMet2 was more efficient in controlling the comminution specific energy. Therefore, the implementation of mass movement limitations allied to the use of stockpiles favored the optimization of the mine scheduling results. It was possible to verify the importance of including the variable comminution specific energy in the block model, to provide more realistic and reliable results.

Keywords: Mass stabilization; Stripping ratio; Strategic mine planning; Global optimization.

Metodologia para incluir a energia específica de cominuição no planejamento estratégico de mina a céu aberto usando otimização global

Resumo

O Planejamento Estratégico de Mina exige um conhecimento apurado do depósito mineral, sendo essencial a utilização de modelos de blocos apoiados pela Geometalurgia. Atualmente, a metodologia utilizada considera o planejamento subdividido em etapas (determinação da cava final, avanços de lavra, sequenciamento de mina). A otimização global pode garantir a solução ideal, uma vez que todas as etapas são resolvidas em conjunto. No presente estudo, utilizou-se o banco de dados Marvin, considerando a inclusão da variável geometalúrgica energia específica de cominuição. No primeiro cenário, denominado GeoMet1, foi incluído um *ramp-up* nos primeiros três anos. No GeoMet2, foram definidas diferentes faixas de movimentação máxima, bem como a implementação de pilhas de estoque de minério e seu posterior remanuseio. Ganhos de 9,66% no VPL e 5,18% na produção de minério foram encontrados para o GeoMet2. O segundo cenário apresentou produção de minério aderente ao programado, além de maior estabilidade na relação estéril/minério. Além disso, o GeoMet2 foi mais eficiente no controle da variável energia específica de cominuição. Portanto, a implementação de limitações de movimentação de massa aliada ao uso de pilhas de estoque favoreceu a otimização dos resultados de sequenciamento de mina. Foi possível verificar a importância da inclusão da energia específica de cominuição no modelo de blocos, para fornecer resultados mais realistas e confiáveis.

Palavras-chave: Estabilização de massas; Relação estéril/minério; Planejamento estratégico de mina; Otimização global.

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1 Introduction

The pioneer methodology of mine planning was developed by Lerchs and Grossmann [1], which nowadays is used in most mining companies. It consists, starting from a block model of the deposit, of the following steps: ultimate open pit limit, delimitation of nested pits and pushbacks. According to Whittle et al. [2], the ultimate open pit is defined by considering the extraction of all blocks at the same time and without applying discount rates. After defining the pushbacks, a parameterization process is carried out to generate the mine scheduling. Global optimization, in turn, is an improvement of Direct Block Scheduling (DBS), initially conceptualized by Johnson [3]. It considers integrated mathematical formulations, building the ultimate open pit and mine scheduling in a compact and leaner process [4].

According to Macfalarne and Williams [5], understanding the geometallurgical variables throughout the deposit allows for anticipating improvement actions and, consequently, earning gains in NPV and production. However, the benefits of including geometallurgical variables in the block model need to be further investigated. In this context, a work done by Morales *et al.* [6] can be highlighted. That paper presents mine planning simulations performed incorporating the comminution specific energy to the block model. Gains above 9.4% in NPV were demonstrated, as well as a reduction in operating costs compared to scenarios where the deposit did not take into account geometallurgical parameters.

In mine planning it is necessary to manage some parameters to stabilize ore and waste production throughout the Life of Mine (LOM). In the present paper, the following parameters were highlighted: *ramp-up*, stripping ratio and use of ore stockpiles.

1.1 Ramp-up particularities

According to Haller [7], *ramp-up* is the process of gradually increasing production in the first years of the LOM. Such production scheduling allows for the stabilization of production and the quality of the product to be processed [8]. Maher and Medini [9] say that strategy is fundamental for the maturation of the project, as well as the consolidation and adjustments of the response variables of the planning.

1.2 Relationship between stripping ratio and open-pit parameters

Stripping ratio (SR) can be defined as the ratio between the amount of waste mass to be extracted for a unit of ore mass released [10]. This parameter varies along with the mine scheduling, depending on open-pit geometric constraints that guarantee operational stability and safety. The definition of mass movement goals by production periods makes it possible to manage the SR along with the LOM [11].

SR must be controlled within acceptable limits, to keep the Net Present Value (NPV) within the expected range and guarantee the release of the ore needed by the plant. NPV is an important parameter for the economic evaluation of mine planning scenarios. This variable integrates the discounted cash flows over time, updating these values to the present moment and allowing the assessment of the financial return of a project over the LOM [10]. One of the factors that influence SR is the acceptable slope angle in each mine lithology [12].

Abdellah et al. [13] demonstrated a method capable of selecting the optimal general slope angle of open-pit mines according to the following parameters: safety, productivity and mine costs. The results demonstrate increasing profitability and decreasing stripping ratio cost as the overall slope angle becomes steeper.

1.3 Use of ore stockpiles in mine projects

The ore stockpiles allow the continuity of mining, allowing the improvement of mining productivity and blending of different ore grades. Other advantages of ore stockpiling can be listed: reduced run-of-mine parameter variation and gains in plant operating parameters, such as energy consumption in comminution and process recovery [14]. However, implementing stockpiles requires additional handling costs. In this way, the decision to use stockpiles demands a previous economic evaluation of these expenses in relation to the expected gains.

Regarding formation and rehandling, the stockpiles must have narrow grade bands, in addition to being sequenced to facilitate the ore blending process. Additionally, they must have a pre-defined particle size distribution to minimize the variability of energy consumed in milling. Proper mine programming ensures acceptable plant feed quality, contributing to prolonging the LOM [15].

1.4 Objective and contributions of this research

The objective of this work is to investigate, using the global optimization approach, a methodology capable of including the geometallurgical variable comminution specific energy in open-pit mine planning. In the scientific literature, there are few articles dealing with these issues with consistency, then this research is trying to fill this gap. The following conditions were considered: *ramp-up*, different ranges of maximum mass movement and use of ore stockpiles.

2 Materials and methods

2.1 Software used

For the development of the scenarios, a software called MiningMath® v2.3.21 was used. This software is based on the global optimization methodology, being able to optimize the ultimate open pit and generate mine scheduling. Its algorithms include mathematical formulations and proprietary heuristics [16].

2.2 Marvin block model

The Marvin public block model, available on the Minelib website [17], was used for that study. It consists of a copper and gold deposit composed of 53,271 blocks whose dimensions are equal to 30 m x 30 m x 30 m and the following variables per block: position (indices X, Y and Z), economic values (USD), copper (%) and gold (ppm) grades, density (t/m^3), slope angle (degrees) and fixed process recoveries (88% for copper and 60% for gold). According to MiningMath® [16], the economic parameters of each block are calculated by the user, being treated as input data. The destinations are defined by mathematical models, depending on the economic values of each block, which are: process, stockpile or waste.

2.2 Scenarios studied

This work sought to deepen the investigation started by Mata et al. [18]. In this paper, a mine planning scenario was developed and applied to the Marvin block database, including the geometallurgical variable comminution specific energy and under certain assumptions and constraints. In the study presented here, two distinct scenarios were established for mine planning, considering new parameters cited ahead. The first scenario, called GeoMet1, considered a *ramp-up* in the first three years of ore production, keeping constant the maximum mass moved in the mine. The second scenario called GeoMet2, in addition to the assumptions and constraints adopted in GeoMet1, took into account gradual values of maximum movement tonnages throughout the LOM. In addition, the creation of a regulation stockpile was included in the scenario, with a rehandling cost equivalent to 10% of the mine cost (0.09 USD/t). This value was based on the author's experiences in real mining projects. Borges [19] pointed out that the ore stockpiles must be established from the mine planning, as well as the associated costs must be compatible with the mine costs, production levels and quality foreseen in the project. Zhang and Kleit [20] studied an economic model for ore stockpiling in two stages (formation and rehandling for plant feeding). It was possible to demonstrate significant financial gains thanks to the use of stockpiles, indicating that the benefits obtained outweigh the additional costs of rehandling. Otherwise, gradually increasing Stripping Ratio ranges allowed to verify how that limitation affects the simulation results, as well as the stockpiling procedure aims to stabilize the ore mass fed into the plant. A compliance target was adopted for the annual ore masses defined. The minimum acceptable compliance was 90%, during and after the ramp-up. Table 1 presents the values adopted for the operational constraints.

An installed power for grinding equal to 37,000 kW was considered for ore comminution. To generate the values of comminution specific energy variable per block, the deposit was divided into 17 levels, considering an increasing correlation between the comminution specific energy and the mine depth. It is known that deeper rocks remain fresher and unaltered, presenting greater hardness. For the most superficial level, an energy of 10.0 kWh/t was assigned, with increments at each level until reaching 17.0 kWh/t at the deepest level. Equation 1 shows how the throughput for each block can be estimated.

$$T = \frac{P}{E} \tag{1}$$

Where: T = Throughput (t/h); P = available motor power (37,000 kW); E = comminution specific energy (kWh/t).

Table 1. Operational Constraints

Constraint	GeoMet 1		GeoMet 2	
Range of Cu grades on the process plant feed (%)	0.3	0.7	0.3	0.7
Range of Au grades on the process plant feed (ppm)	0.3	0.7	0.3	0.7
Slope Angle (º)	45		45	
Minimum mine width (m)	100		100	
Minimum bottom width (m)	100		100	
Maximum vertical rate of advance (m)	150		150	
Discount rate (%)	10		10	
Maximum moved tonnage of the mine (t) – from year 1 to year 6	60,000,000		40,000,000	
Maximum moved tonnage of the mine (t) – from year 7 to year 12	60,000,000		45,000,000	
Maximum moved tonnage of the mine (t) – from year 13 to year 15	60,000,000		50,000,000	
Maximum moved tonnage of the mine (t) – from year 16 onwards	60,000,000		60,000,000	
Maximum processing tonnages - first year: 70% (t)	14,000,000		14,000,000	
Maximum processing tonnages - second year: 80% (t)	16,000,000		16,000,000	
Maximum processing tonnages – third year: 95% (t)	19,000,000		19,000,000	
Maximum processing tonnages - after *ramp-up* (t)	20,000,000		20,000,000	
Overall processing time (hours)	7,884		7,884	

For each block, the processing time in the plant will be calculated by Equation 2.

$$TP = \frac{M}{T} \quad (2)$$

Where T_P = processing time (h); M = block mass (t); T = throughput (t/h).

The increase or decrease in processing time causes changes in the cost of the process. It is known that the residence time of each block in the comminution circuit influences both the consumption of electricity and the level of wear of equipment such as crushers and mills. Therefore, it was considered a direct dependence of the process cost in relation to the T_P. For T_P = 21.9 h, which corresponds to the average value of the model, a process cost of 4.0 USD/t was assigned. For blocks with higher or lower T_P, the process cost was calculated proportionally. Table 2 presents the input parameters used.

3 Results and discussion

Table 3 presents a summary of the overall simulation results.

Figure 1 expresses the evolution of the NPV for the 2 scenarios.

Table 2. Input parameters

Input parameters	Cu	Au
Recovery	88%	60%
Comminution specific energy (kWh/t)	Variable	
Processing Time (hours)	Variable	
Process Cost (USD/t)	Variable	
Mine Cost (USD/t)	0.9	
Handling cost (USD/t)	0.09	
Selling Price (USD)	7,034.00	59.70
Selling Cost (USD)	720	0.20

It is noticed that there is an abrupt reduction of the NPV increments from year 7, both for GeoMet1 and GeoMet2. This fact is justified due to the increase in the depth of the open pits, causing an increase in the comminution specific energy and process costs. Note that the GeoMet 2 scenario performs higher NPV values since the beginning of the project, presenting a final gain of 9.66% compared to GeoMet1. This positive result is due to the stabilization of ore production per year and greater use of the mineral deposit, resulting from the formation and subsequent rehandling of stockpiles in the mine. There is an additional cost in this operation, but some advantages tend to favor greater profitability. It can be mentioned, in this case, improvements in the blending of ores of different grades and the reduction of oscillations in the stripping ratio. Figure 2 presents the ore production and Stripping Ratio (SR) for the two scenarios.

It is verified that GeoMet 2 presents ore productions adherent to the established target during the entire LOM, while GeoMet 1 presented production drops in years 9 and 20. In fact, the average % compliance of GeoMet 2 in the period after the *ramp-up* was 5.93% higher than that found by GeoMet 1. Therefore, the use of intermediate stockpiles

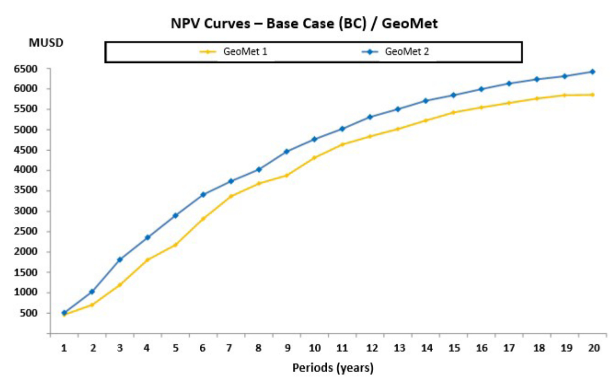

Figure 1. Evolution of the NPV for the simulations performed.

Table 3. Simulation results

Result	GeoMet 1	GeoMet 2	Deviation (%)
Number of periods (years)	20	20	0
% Compliance to ore target in the *ramp-up* – year 1 (%)	99.99	98.91	-1.09
% Compliance to ore target in the *ramp-up* – year 2 (%)	98.22	100.00	+1.81
% Compliance to ore target in the *ramp-up* – year 3 (%)	99.99	100.00	+0.01
% Compliance to ore target – average after the ramp-up	93.56	99.11	+5.93
NPV (MUSD)	5,859.1	6,425.1	+9.66
Plant Feed (Mt)	366.81	385.81	+5.18
Waste (Mt)	398.37	425.46	+6.80
Stripping Ratio (SR)	1.09	1.10	+1.54
Global Mass Movement (Mt)	765.18	811.27	+6.02
Average Processing Time (h)	6,679.6	7,050.5	+5.55
Average Cu grade - Ore (%)	0.485	0.479	-1.18
Average Au grade - Ore (ppm)	0.459	0.478	+4.25
Average Cu grade - Waste (%)	0.077	0.079	+3.97
Average Au grade - Waste (ppm)	0.080	0.077	-3.90

was beneficial for the regularization of the masses fed into the plant. The GeoMet 2 scenario delivered 5.18% more ore production than GeoMet 1.

Regarding the SR, the GeoMet 1 scenario presents great instability in two distinct phases. From year 1 to 9, there is a tendency to increase this parameter. The lowest value was 0.05 in year 2, and the maximum peak was 2.11 in year 9. From year 10 onwards, the values fluctuate downwards until reaching zero in year 20. GeoMet 2, in turn, exhibits a more stable three-step behavior. From year 1 to 9, it varies in the range of 0.51 to 1.31. Between years 10 to 16, he works between 1.31 and 1.91. From year 17, it drops abruptly until reaching 0.25 in the last year. Thus, the implementation of intermediate stockpiles allowed the development of the mine in a more cadenced and stable way, which certainly brings greater predictability to mine and process plant operations.

Figure 3 shows the global movement of mine masses and stockpiles for both scenarios. With regard to the GeoMet 1 scenario, it can be seen that the global movement of mine masses oscillates significantly. Until year 9, there is a tendency for this parameter to increase, in line with the increase in SR seen in Figure 2. From year 10 onwards, monthly movements tend to decrease, until reaching 3.08 Mt, corresponding to the production of residual ore in the open pit.

GeoMet 2, in turn, has four distinct phases, the first three of which adhere to the goals outlined in Table 1. From years 1 to 6, the annual moving mass is around 40 Mt. Between years 7 to 12, it makes about 45 Mt per year. From 13 to 15 years, it reaches up to 50 Mt. In year 16, this parameter drops from 60 Mt to 8.14 Mt, indicating a significant reduction in the development of the mine. During the LOM, there was the formation and posterior rehandling of ore stockpiles, contemplating a global ore mass of 47.79 Mt. Therefore, the use of stockpiles combined with the definition of narrower ranges of mass movement disciplined the mine operation without harming the supply of the plant. Figure 4 presents the comparison of the open pits generated in years 6, 12 and 18.

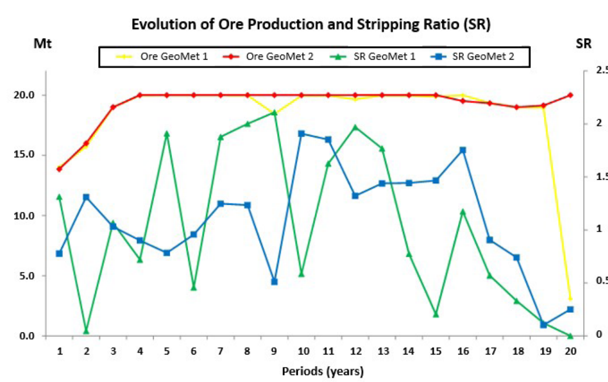

Figure 2. Ore and waste extracted by each year.

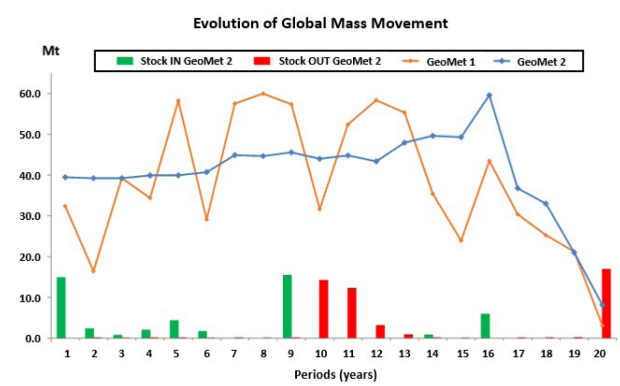

Figure 3. Evolution of global mass movements during the LOM.

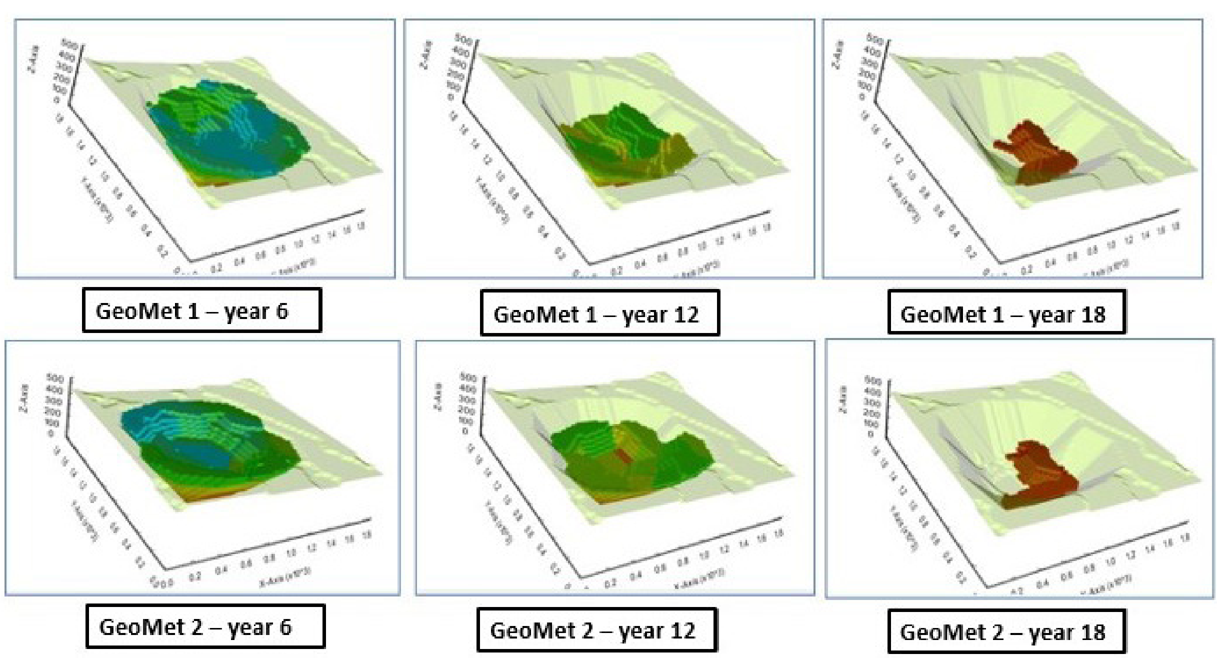

Figure 4. Evolution of open pits in the years 6, 12 and 18 for both scenarios.

With respect to years 6 and 12, GeoMet 2 has a more regular open pit configuration than GeoMet 1. Mine development, in the second scenario, evolved both in the center and in the lateral parts of the mineral deposit, while in GeoMet 1 the extraction was more accentuated in certain peripheral regions of the deposit. This strategy favored a better blending of regions with blocks of different energy specific comminution, allowing greater control of processing time in the plant. Therefore, GeoMet 2 obtains a better use of the deposit and more suitable blends, thanks to the use of stockpiles and the definition of narrower bands of mass movement by periods. In year 18, closer to the end of the LOM, this effect is not visible since the deposit is close to exhaustion and there are not many fronts available.

4 Conclusions

The GeoMet 1 and GeoMet 2 scenarios allowed describing and analyzing a methodology for the inclusion of the geometallurgical variable comminution specific energy in the block model. This topic, despite being very important to increase the reliability of mine planning, has not been adequately considered in practice. It was possible to verify the feasibility of establishing a *ramp-up*, progressive ranges of mass movement in the mine and ore stockpiles in the scenarios. GeoMet 2, which adopted consecutive mass movement limitations throughout the LOM and considered the formation and rehandling of ore stockpiles, achieved 5.18% higher global ore production as well as 9.66% higher NPV than GeoMet 1. There was also a stabilization of the stripping ratio, ensuring greater predictability in the mine planning and operation. The movement of 47.79 Mt of ore stockpiles was staggered over several years, blending on the feed of plant to maintain stability for processing. In this way, the composition and subsequent rehandling of the ore stockpiles allowed the optimization of the development of the mine, ore blending and feeding of the process plant. The deepening of open pits, from year 7 onwards, brought the extraction and processing of blocks with greater comminution specific energy and, with that, increased process costs and reduced NPV increment.

However, the GeoMet2 scenario was more efficient in this matter, as the use of ore stockpiles and stabilization of the stripping ratio allowed the mitigation of variations in processing time. As a contribution, the research showed that the use of geometallurgical variables distributed in the block model brings greater accuracy and effectiveness to the performed mine planning scenarios, adequately subsidizing the decision-making.

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References

1 Lerchs H, Grossmann IF. Optimum design of open pit mines. In: Joint CORS and ORSA Conference; 1965; Montreal. Montreal: Transactions CIM; 1965. p. 17-24.

2 Whittle D, Whittle J, Wharton C, Hall G. Strategic mine planning. 8th ed. Vancouver: Gemcom Software International Inc., 2005.

3 Johnson TB. Optimum open pit mine production scheduling. Berkeley: Operations Research Department, University of California, 1968, p. 120.

4 Ota RRM, Martinez LA. SimSched Direct Block Scheduler: A new practical algorithm for the open pit mine production scheduling problem. In: Conference APCOM 2017; 2017; Colorado. Colorado: APCOM; 2017. v. 38.

5 Macfarlane AS, Williams TP. Optimizing value on a copper mine by adopting a geometallurgical solution. Journal of the Southern African Institute of Mining and Metallurgy. 2014;114(11):929-935.

6 Morales N, Seguel S, Cáceres A, Jélvez E, Alarcón M. Incorporation of geometallurgical attributes and geological uncertainty into long-term open-pit mine planning. Minerals. 2019,9(2):108. http://dx.doi.org/10.3390/min9020108.

7 Haller M. Cycle time management during production ramp-up. *Robotics and Computer Integrated Manufacturing*, 2003;19:183-188.

8 Mohr SH. Projection of world fossil fuel production with supply and demand interactions [thesis]. Newcastle: The University of Newcastle. 2010.

9 Maher DR, Medini K. A preliminary overview of ramp-up management practices in crisis context. In: APMS 2021: Advances in Production Management Systems. Artificial Intelligence for Sustainable and Resilient Production Systems; 2021; Nantes, France. Korea: APMS; 2021. p. 484-492.

10 Hustrulid W, Kuchta M. Open pit mine – Planning & design. 2nd ed. Rotterdam: Balkema; 2006. v. 1.

11 Wyllie DC. Rock slope engineering: civil and mining. 5th ed. Boca Raton: CRC Press; 2017. 568 p.
12 Marndi B. Stability of slopes in iron ore mines [thesis]. Rourkela: Deemed University; 2011.
13 Abdellah WR, Hirohama C, Sainoki A, Towfeek AR, Ali MAM. Estimating the Optimal Overall Slope Angle of Open-Pit Mines with Probabilistic Analysis. Applied Sciences (Basel, Switzerland). 2022;12:4746. http://dx.doi.org/10.3390/app12094746.
14 Miola W. The case for the homogenization of stockpiles. Brasil Mining Site; 2022 [cited 2022 Oct 5]. Available at: brasilminingsite.com.br
15 Prasojo TS, Yulianto A, Hindarto A, Parinussa B, Arifien A. Ore blending as mine scheduling strategy to accommodate resources conservation at pakal nickel mine, PT ANTAM (Persero) Tbk. Procedia Earth and Planetary Science. 2013;6:24-29.
16 MiningMath®. MiningMath's Knowledge Base. 2021 [cited 2021 Nov 10]. Available at: https://knowledge.miningmath.com/
17 Espinoza D, Goycoolea M, Moreno E, Newman AN. MineLib: a library of open pit mining problems. Annals of Operations Research. 2012;206(1):91-114. [cited 2012 Nov 1]. Available at: http://mansci-web.uai.cl/minelib/
18 Mata JFC, Nader AS, Mazzinghy DB. Inclusion of the geometallurgical variable specific energy in the mine planning using direct block scheduling. Tecnologia em Metalurgia, Materiais e Mineração. 2022;19:e2677.
19 Borges TC. Análise dos custos operacionais de produção no dimensionamento de frotas de carregamento e transporte em mineração [dissertação]. Ouro Preto: Universidade Federal de Ouro Preto; 2013.
20 Zhang K, Kleit AN. Mining rate optimization considering the stockpiling: a theoretical economics and real option model. Resources Policy. 2016;47:87-94.

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