Influence of water level in mine sequencing applied to strategic mining planning

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Abstract

Developing mine sequencing involves a number of factors and a large amount of information, and consequently the profitability of the project will strongly depend on the production schedule. A mining project may be conditioned to non-optimal sequencing, which may affect the economic results of the project and also lead to an inadequate utilization of the mineral resources. The conventional method of mining sequencing is divided into three main steps: first, the delineation of the final pit; second, subdivision of the final pit in operational pushbacks (mining advances) and third, sequencing the blocks in each of these pushbacks, taking into consideration mine, processing plant and market capacities. However, there are some aspects that are not usually incorporated in production scheduling, including ore mining below groundwater level. The objective of this study is to demonstrate the relevance and impact on the results of the Net Present Value (NPV) from groundwater level as a constraint related to the need for its drawdown, also considering grades and Stripping Ratio (SR) variability during mining sequence for a phosphate mine. The results show a difference of U$ 140 million for the evaluation considering and not considering groundwater level, without considering other restrictions.

keywords: sequencing, mining, groundwater, mineral economics.

1. Introduction

In accordance with Hartman and Mutmansky, (2002), open pit mining is a method of operating a surface mine which is simple in concept but complex in its cost and efficiency requirements. Therefore, Samis (2001), Dessureault *et al*., (2007), Dehghani and Ataee-pour, (2012) emphasize that mining projects demand constant risk assessment. This is because the value of the project is influenced by many uncertainties such as economy (commodity price, operating costs, production sequence, discount rate), geology (contents, density, hydrogeology, hardness) and underlying physical issues (environmental concerns, leasing limits). Therefore, evaluating and estimating a mine project without mentioning the risk of future losses (or opportunities) may lead to unsatisfactory results.

Mineral deposits have their formation dictated by natural laws which present several challenges and conflicts that should be better investigated to comply with the needs of the mining enterprise. The distribution of variables representing the quality of minerals, such as grain size, grade, groundwater level and amount of waste to be removed may hinder or even make the economic exploitation of a mineral deposit impossible. In this respect, the conventional method for open-pit planning starts with modeling the orebody based on the borehole data and geological information. Then, the mining field is divided into blocks of regular volume. Akbari *et al*., (2009) comment that a mineral reserve is that part of the resource that meets minimum physical and chemical criteria related to the specified mining, production practices, and can be reasonably assumed to be economically, and legally extracted, or produced at the time of determination. Hence, the reserve of an open pit mine can be estimated after ultimate pit determination and cut-off grade calculation, which directly depend on the price of final product. Therefore, Evatt *et al*., (2012) highlight the uncertainties of the mineral reserve estimate and their effects on the duration of the enterprise.

Gholamnejad *et al*., (2007) state that long-term production planning design is a major step in mine planning because it determines the economic outcome of a project. Also long-term planes act as a guide for medium and short-term production scheduling. Because there are a large number of blocks within the ultimate pit limit, the pit can be divided into a series of sub-pits commonly called pushbacks, cutbacks or phases. They are designed with haul road access and act as a guide during the yearly scheduling process. Therefore, pushback design plays a key role in defining annual cash flows to be generated from a mining operation. There may be many alternative pushback sequences for an open pit, which can result in obtaining different NPV from a mining project. According to Asad *et al*. (2014), owing to the large scale of open pit mining operations, the optimal long-term planning, in the context of production phase design (pushbacks) and production scheduling, is a complex technical challenge. Meagher *et al*., (2009) comment that due to the advance of simulation techniques, new methods for producing ultimate pit limits and pushbacks are needed for multiple realizations of the same deposit. Averaging the multiple realizations into a single model and using the traditional techniques does not leverage some of the upside available from the simulations.

Hustrulid and Kuchta (2013) summarizes it: long-term planning of a typical open pit mining operation involves three sequential steps: (i) developing a three-dimensional orebody model that consists of an accumulation of mining units (blocks) with their available metal content (quality) and tonnage (quantity); (ii) accomplishing production phase design, i.e. a phase-wise sequence of extraction that reaches the ultimate pit limit or overall extent of extraction; and (iii) scheduling production of mining blocks within each phase subject to the physical mining and processing constraints.

Mine planning aims at the rational use of mineral deposits and project profitability involving the application of a set of techniques for decision-making and the selection of the best alternatives for mine life whose goal is to achieve the best production sequence. Abdel Sabour and Dimitrakopoulos (2011) reckon that, commonly, there may be alternative, technically feasible mine plans available that meet operational and technical constraints. The selection among those plans is then based on economic reasons. This is carried out by evaluating each of the possible mine plans and comparing their economic attractiveness so as to select the most economically appealing one.

Mine planning allows to anticipate the occurrence of problems which can be avoided in the future or at least minimize its consequences. Dimitrakopoulos and Ramazan (2004) affirm that the optimization of long-term production sequencing is important for managing the cash flows inherent to open-pit mining ventures. In terms of ore, tons and quality, the discrepancies between actual production and planning expectations are caused by uncertainties about the orebody. As it is an anticipated simulation of the mining routine, this planning permits to know a *priori* the possibility of controlling quality variables, evaluate groundwater level behavior over time and the best use and allocation of mining equipment. Moreover, it enables to establish the schedule of waste generation/disposal and/or tailings, providing subsidies for better use of the mineral resources, seeking to minimize the environmental impact.

Problems can occur in non-planned mining such as ore exploitation with an average grade above the necessary, which will irreparably impoverish the remaining reserve and prematurely exhaust the mine, due to the removal of overburden poorly planned or immediate mining without taking into account the future of the ore availability. Another increasingly common constraint in mining operations is the control of groundwater level because of the gradual deepening of the pit bottom. This may hinder mine operations in some sectors or even in the whole mine for a certain period of time.

This article aims at evaluating the impacts of possible constraints, especially water level, on the ore grade and SR oscillations. These impacts are analyzed based on the results of NPV obtained in each mine sequencing.

2. Materials and methods

Considering that mine sequencing is essential to the success of a mining entrepreneurship, the methodology used in this study focused on maximizing the financial return for the mining business, especially in the early years of mine operation. Thus, the delineation of the final pit involves some crucial steps, such as a representative block model, well-adjusted profit function, a consistent cut-off grade with the available mineral reserves and technology. Mine sequencing requires some additional input data, such as current topography, production rates and possible constraints as follows: the search of ore providing stability in the average grade fed to the process, the search for stability in SR, the vertical feed control considering groundwater level, environmental limit of pit depth and mining leases.

According to Osanloo *et al*., (2008), mine sequencing begins with the determination of the production capacity based on mine operational capacity, the estimates for operating costs and commodity prices. Then, using block model and the economic evaluation of each block, an algorithm analysis of the positive blocks as well as the overlying waste units in order of precedence should be made to check if its extraction is economically justifiable. This analysis is based on the cutoff grade which checks if the undiscounted profit obtained from a given ore block can pay the cost to remove the necessary waste blocks. The final pit is then determined using an optimization algorithm in order to maximize the undiscounted cash flow. Within the final pit, some phases are designed so that the reserve is divided into multiple nested pits. These procedures are a parameterization using revenue or cost factors to generate smaller pits, for example, from lower revenue per ton of ore, and then moving to higher pits with higher revenue per ton of ore. Subsequently, operational constraints are imposed in order to generate the so-called operational advances also known as *pushbacks* which are mining advance areas to reach the final pit. They are used as guidelines during the annual production schedule planning. Before determining the extraction sequence, a cut-off grade should be set in order to differentiate ore and waste allowing for the elaboration of the production plans.

Dagdelen (2001) informs that there is a number of sophisticated software packages in the mining industry, which can outline the final pit, perform analysis, do pushback design and determine annual mining plans. However, it is important to highlight that not all of these steps may be optimized by a single program due to large changes in mathematical scale. The most common approach to this problem is dividing it into sub-problems similar to those shown in Figure 1. In this study the software NPV Scheduler was used to outline the final pit, and Studio Op, for visualizations and design, both by Datamine. According to the company, both software work with mixed algorithm and are based on Lerchs and Grossmann (1965).

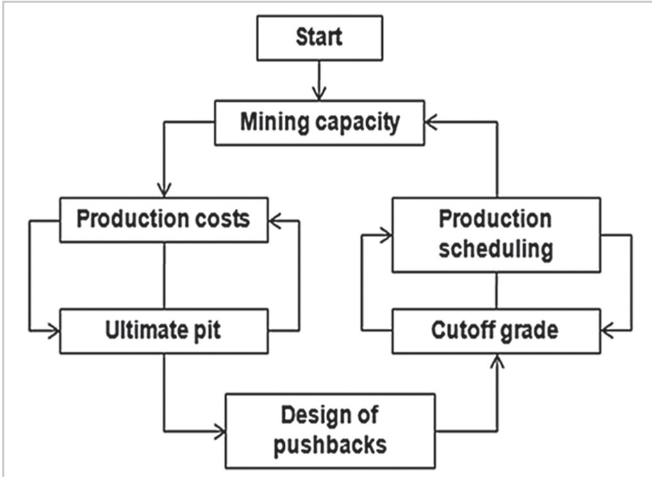

Figure 1 - Steps of traditional planning by circular analysis. Source: (Dagdelen (2001)).

The main point used to develop this methodology was determining and ranking the most relevant constraints after measuring the project outcome using NPV. The structure of the methodology proposed herein can be seen in Figure 2. The following steps were taken: (i) determination of the input block model; (ii) final pit definition; (iii) pushbacks were designed primarily with the maintenance of default input parameters suggested by the sequencing software; (iv) NPV was assessed considering only the processing plant capacity; (v) some mining scenarios were simulated imposing constraints, such as ore grade and stripping ratio, both individually and later on simultaneously; (vi) the procedure was repeated by changing the number of pushbacks, starting again from pushback designs. The new sequencing scenarios were simulated from the following number of pushbacks: 3, 5, 7, 10, 12, 15, 17, 20, 22, 25 and 100. For each scenario, evaluation and comparison of NPV were carried out.

Finally, groundwater level was added to establish a new final pit providing that water level elevation, given by a drawdown model at the end of mine life, overlies the original final pit bottom. Thus, the analysis considering this constraint initiated with a new ultimate pit scenario generated by the intersection of the prior pit limit and water level. Finally, the alternatives were compared not only in terms of NPV, but also the average grades fed to the plant and the stripping ratio for the first 10 years of mine sequencing.

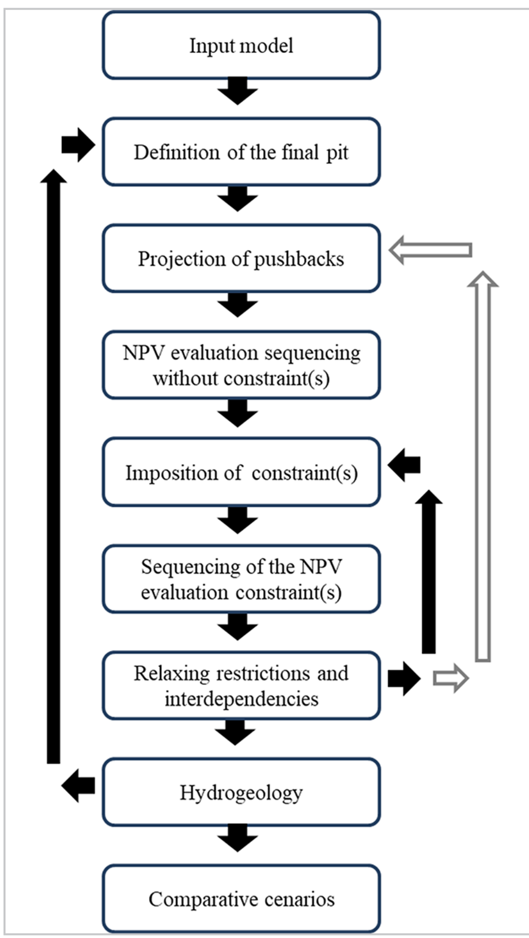

Figure 2 - Methodology used in this work.

3. Case Study

In order to illustrate the methodology, a case study was carried out in a phosphate deposit located in Araxá Minas Gerais, southeastern Brazil. The phosphate deposit belongs to the Barreiro carbonatite complex, named F4. It was designed to feed plant II in the Complex with capacity to process around 3.2 million tonnes per year. A reconstruction of the original topography of the mine within the leasing limit, granted to Vale Fertilizantes, was necessary. Leasing limit is a physical polygon in which neither final pit nor mining operations can exceed in any mining scenario. Figure 3 shows the topography and leasing limit.

The block model has the following dimensions: 25m x 25m x 10m (x, y, and z, respectively) containing 6 typologies: #1 undefined, #2 oxidized ore, #3 cemented ore, # 4 friable silica-carbonated ore, #5 hard silica-carbonated mineral rock and #6 waste. The ore consists of grouping types 2 and 3 and waste by the conjunction of the other types.

The surface drainage is calculated considering the average monthly runoff comprised by part of the total amount of rainfall in the entire area of the natural contribution area, where the mine pit is inserted, plus the runoff from the mining area of the adjacent company which flows into F4 pit. Considering historical precipitation, a minimum of 372 m^3/hour water pumping capacity is needed, reaching the flow rate of up to 1.231 m^3/hour during the rainy season. However, when taking into account the maximum historical 30-year monthly precipitation, the water flow can reach rates ranging from 1.105 to 2.532 m^3/hour up to the exhaustion of the mine. In order to avoid very high flows in the pit, a peripheral channel drain located next to crest of the final pit is usually suggested so as to contain the water income from the external portion of the natural drainage area, reducing the volumes to be pumped out from the pit bottom.

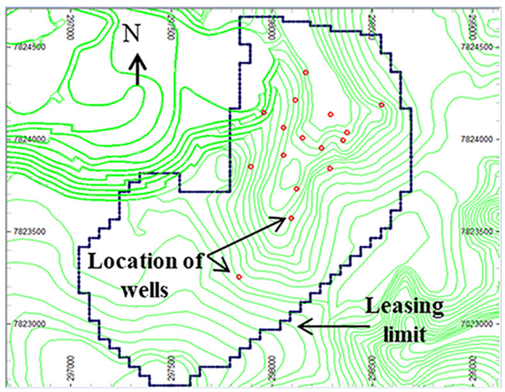

Figure 3 - Original topography in the region of the mine area in September 2009 with the wells location (red dots).

A numerical model of transitional arrangements was developed to simulate the water level during the mine life and calibrated for simulating groundwater level drawdown. The purpose of this process is to measure and assess the impact of drainage structures and to also guarantee the water level below the pit bottom, whereby the pumping flow rates needed are quantified and possible drawdown impacts identified. This type of simulation is useful to determine minimum pumping requirements during the mine advancement and also to estimate the number of minimal wells and their location to proceed with drawdown. The best and most realistic scenario consists of the combination of drawdown wells with dewatering channels in the lower levels of the pit, directing the runoff towards a sump located at the bottom pit where the water is pumped out. This method is advantageous because it considerably reduces the number of required wells, although it creates operational difficulties. F4 is located alongside the Barreiro Hydro mineral Resort where there are several water springs. Therefore, the pit bottom cannot be deepened below 980m elevation, as lowering the water level beyond this limit can interfere with the stream flow rate.

Finally, based on the above listed data and profit function calculation (assumption made for mining and process costs, commodity price and process recovery), provided by the company and kept confidential by request, mining sequencing was performed. The first step was importing the block model and selecting the working variables, in this case P_2O_5 (phosphate grade). In the subsequent step, the economic model was generated consisting of an ore grade block model and the economic value for each block.

Within the pit limit, the pushbacks must be sequenced according to annual ore demand respecting the available budget. This is an important step during mine planning to optimize NPV for each scenario considered. So, it is also essential to manage parameters such as: average ore grade consistent with the available technology in the processing plant, waste tonnes to be removed per year and groundwater level inside the mining areas. An alternative to control these variables in mine sequencing is adjusting pushbacks according to the variation of such constraints. After the pushback adjustment, it is possible to program the sequence of annual exploitation. In this case study, the first 10 years of mine operation were analyzed due to the availability of the hydro geological model information.

4. Results and discussion

4.1 Final pit / mine sequencing

The final pit limit represents a boundary in which ore mass and the associated amount of waste can be profitably mined, according to predefined parameters. The economic value of a final pit and its respective limit are used as a benchmark to compare with the later stages of sequencing. The values found in the final pit base case were 78.3 Mt of phosphate ore with a stripping ratio of 2.87 (t/t). When groundwater level was considered as a constraint in sequencing, it was necessary to establish a new final pit shell since the water level surface was overlying the original final pit bottom in some places. This "new" pit bottom considered the results of the numerical model simulating the groundwater level drawdown which was based on the number and the flow rates estimated for each drawdown well. The output surface now became the intersection between the original final pit bottom and the simulated water level. The result of the new final pit was 51.0 million tonnes of ore with 4.20 (t/t) SR.

After importing all the data and following all the steps described in the methodology, it is possible to choose the number of pushbacks to work with. Provided that this is an important step in mine sequencing and that the ideal value to be used is not known, a number of scenarios were simulated in order to find out the optimal number of pushbacks. Thus, the scenarios were simulated with the following number of pushbacks: 3, 5, 7, 10, 12, 15, 17, 20, 22, 25 and 100.

4.2 Mine sequencing without constraints

Before starting to impose constraints in mine sequencing (grade, SR and groundwater level), it is important to assess the NPV of the project in order to define a reference for comparison. That is why, later on in this study, a mine sequencing without a constraint, but controlling the ore mass which feeds the processing plant was performed. The results are shown on the black curve in Figure 4. All scenarios were simulated with the same software parameters, changing only the number of pushbacks. As shown in Figure 4, when the number of pushbacks is greater than or equal to 15 and less than 25, the NPV of the mine sequencing reaches U$ 690 million. Considering groundwater level, when the number of pushbacks is greater than or equal to 10, the NPV of the mine sequencing varies from U$ 500 million to U$ 550 million as shown by the grey curve in Figure 4.

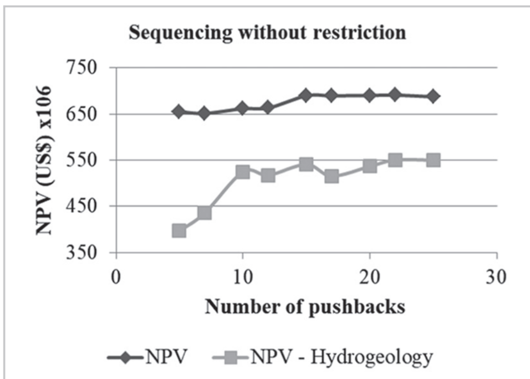

Figure 4 - Comparison of sequencing with and without hydrogeological constraints.

4.3 Mine sequencing considering SR as a constraint

Normally, all treatment plants require a minimum grade so that metallurgical and mass recoveries are kept approximately stable. Figure 5 shows the results obtained from sequencing considering the average P_2O_5 grade of 11.5% with variations of ± 1%, as shown in the black curve. NPV varies according to the number of pushbacks selected. Therefore, the highest NPV found for sequencing was achieved by using 22 pushbacks (U$ 536 million).

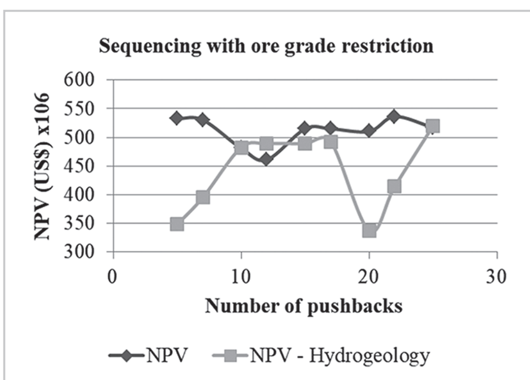

Figure 5 - Comparison of sequencing with and without hydrogeology considering P_2O_5 grade as a constraint.

Considering the same parameters when sequencing with the water level constraint, a value close to U$ 500 million was obtained by selecting pushbacks ranging from 10 to 17 as shown in grey. But with 25 pushbacks, the highest NPV of U$ 520 million was reached according to Figure 5.

It is important to point out that the values that refer to the curve points, considering groundwater level for the sequencing with 20 and 22 pushbacks, are under the tendency line due to the stabilization of SR in which the waste removal values in the last three years are extremely high and impact NPV.

4.4 Mine sequencing considering SR as a constraint

The waste mass to be removed can severely affect a mining project. Minimizing, stabilizing and if possible, delaying the waste quantities to be moved over the years in a mining operation maximize NPV. Figure 6 shows the result of sequencing considering SR as a constraint. It is evident that there is a tendency: the higher the number of pushbacks, the higher the NPV after sequencing. The highest NPV (U$ 643 million) was obtained when sequencing the 20 pushbacks scenario as demonstrated in the black line. Because the final pit, considering hydrogeological constraints, has less ore mass than the original final pit, the reduction of waste is not proportional to the decrease in the ore amount, i.e., the increase of SR from 2.87 to 4.20 makes this aspect extremely important for the profitability of the enterprise. Figure 6 shows the behavior of SR in grey after mine sequencing according to the number of simulated pushbacks. It is quite clear that sequencing with 12 pushbacks provides the highest NPV (U$ 508 million). It must be emphasized that the curve in black does not have the point referring to the sequencing with 25 pushbacks because the software did not generate a new scenario with this amount of pushbacks.

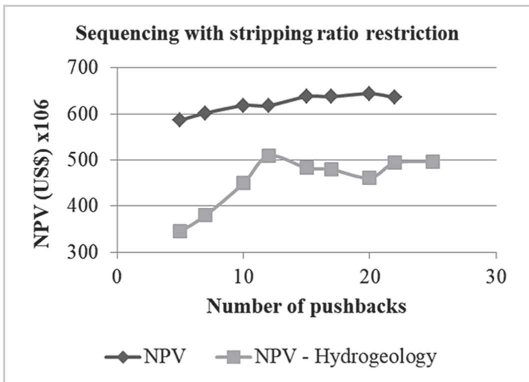

Figure 6 - Comparison of sequencing with and without hydrogeology considering SR as a constraint.

4.5 Mine sequencing considering grade and SR as constraints

Mine sequencing considering grade and SR as constraints was also performed, and it is important to highlight that there is an interdependence between these two variables. By analyzing the black curve in Figure 7, there is no doubt that, from 12 to 20 pushbacks, the NPV of the mine sequencing stabilizes at around U$ 600 million. Mine sequencing for 20 pushbacks achieves the highest NPV (U$ 603 million), considering both grade and SR constraints. In an attempt to stabilize SR at a value closer to the final pit SR, and to obtain an average grade more consistent with the production target, NPV sequencing decreased about U$ 40 million compared to the NPV sequencing considering only SR. As mentioned above, the curve in black does not have the point referring to the sequencing with 25 pushbacks because the software did not generate a new scenario with this amount of pushbacks.

Mine sequencing should be as close to the reality of mining operations as possible, i.e. a schedule that does not take all the available information into consideration, such as limitations in the daily mining operations, entails non-compliance with the annual plan. Hence, if the annual plan is not fully implemented, the whole mine sequencing in the following years will be compromised. The grey curve in Figure 7 shows the NPV sequencing behavior considering hydrogeology. In this case, the sequencing using 12 pushbacks provides the highest NPV (U$ 507 million).

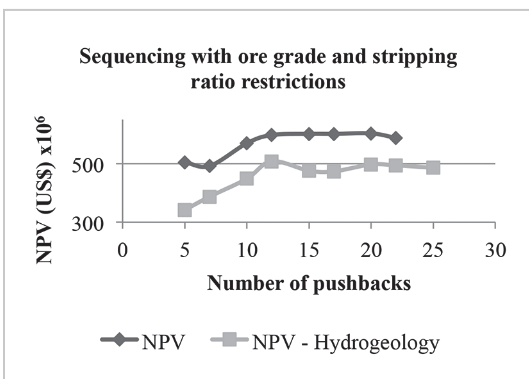

Figure 7 - Comparison of sequencing with and without hydrogeology considering ore grade and SR.

Table 1 shows a comparison of scheduling in the first 10 years for the highest NPV with and without considering hydrogeology for the scenario with ore grade and SR as constraints. Although sequencing deals with different constraints, NPV results, ore grade and SR at the end of 10 years are very close, indicating that the sequencing with hydrogeology was well executed. Therefore, mining operation conditions are more favorable when groundwater level is lowered, which means sequencing considering hydrology.

Table 1 - Comparison of scheduling in the first 10 years for the highest NPV with and without considering hydrogeology for the scenario with ore grade and SR as constraints.

Year	NPV (U$S x 106)		P_2O_5 (%)		Waste (ton x106)		Stripping Ratio (t/t)	
	Nohydro	Hydro	Nohydro	Hydro	Nohydro	Hydro	Nohydro	Hydro
1	0.43	63.09	12.54	12.67	30.13	11.19	9.38	3.48
2	87.83	53.54	12.53	12.19	0.49	10.51	0.15	3.29
3	63.40	61.46	12.61	13.11	7.25	9.88	2.27	3.09
4	50.93	59.20	12.51	13.70	8.78	10.88	2.74	3.40
5	51.61	47.24	13.08	12.97	9.45	10.84	2.95	3.39
6	45.45	44.86	13.08	13.15	9.65	10.21	3.02	3.19
7	42.20	35.28	13.12	12.57	9.55	10.94	2.98	3.42
8	34.51	30.48	12.59	12.23	9.09	10.70	2.84	3.34
9	29.31	27.45	12.42	12.33	9.60	10.99	3.00	3.43
10	32.38	16.24	13.19	11.01	9.41	11.11	2.94	3.47
TOTAL	**438.05**	**438.84**	**12.77**	**12.59**	**103.39**	**107.24**	**3.23**	**3.35**

5. Conclusions

Mine sequencing is the core of mine planning allowing for a strategic view of the pit evolution over time. The constraints and their stabilization attempts have great influence on the pit geometry and hence a huge impact on the project´s NPV. Proper knowledge of the deposit and mining operations are required in the preparation of the production sequence, as failures to comply with the annual plan affects not only the current plan, but also all the way through the established mining sequencing. As demonstrated in the sequencing without regard to hydrogeology, the final pit has 78.3 million tonnes of phosphate ore and SR 2.87 (t/t). When sequencing without considering ore grade and SR as constraints, but taking into account the annual mass fed to the processing plant, the highest NPV was U$ 690.9 million. Considering ore grade as a constraint, NPV was U$ 536 million. Both values were obtained in the simulation with 22 pushbacks. When SR was considered, the highest NPV obtained was U$ 643 million with 20 pushbacks. In turn, considering both constraints, the highest NPV was U$ 603 million. So, these results demonstrate that there is an interdependence between these two variables.

In the sequencing considering hydrogeology, the final pit was rebuilt being reduced to 51.0 million tonnes of ore and the SR increased to 4.20 (t/t). In the mine sequencing considering the annual mass of the processing plant, but without considering ore grade and SR as constraints, NPV was U$ 500 million, in the simulation with 22 pushbacks. For the production schedule with ore grade as a constraint, the highest NPV was U$ 520 million, with 25 pushbacks. In the sequencing considering SR, the highest NPV was U$ 508 million with 12 pushbacks. Taking both constraints, ore grade and SR into consideration, the highest NPV, U$ 507 million, occurred with 12 pushbacks. Again, the interdependence between the constraints of ore grade and SR is evident. Due to the large impact of groundwater level on the project's NPV, regardless of the number of considered constraints, a new simulation study considering the inclusion of drawdown wells is justifiable. As a result, it may be necessary to set up a project to measure the environmental impacts in the mine region, which may lead to an additional request to extend the current groundwater pumping permit provided by the state environmental agency.

In order to demonstrate the accuracy of mine sequencing considering hydrogeology, a comparison of the first 10 years of the production plan was made by comparing the sequencing without considering groundwater level. For this comparison, SR and ore grade were considered as demonstrated in Table 1. The results are very similar as a maximum variation of 4% occurred for NPV, ore grade, waste and SR parameters. It is important to stress that the NPV results obtained are something that can be visually differentiated by presenting completely different mine sequencing. Therefore, it can be concluded that groundwater level as a constraint (hydrogeology) for the first 10 years of sequencing was much more a matter of mining operation management and the fulfillment of annual plans than financial. However, the operation of the mine is facilitated as far as water pumping is concerned, considering the sequencing with hydrogeology.

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