# NPV ANALYSIS OF MULTIPLE SURFACE CONSTRAINTS FOR PIT EXPANSION SCENARIOS

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## ABSTRACT

The operation and management of large surface mines are very difficult and complex tasks. To optimize the entire operation the engineers must deal with several technical aspects and constraints, like orebody modelling, reserves estimation, determination of blending necessity, optimum and operational pit designs, operational costs, environmental issues, among others. In this sense, locating surface infrastructures is one of the most critical mine planning concerns, considering there is always the dilemma between approximating to the pit the processing plant, waste dumps and tailings dam, for example, to reduce the operational costs. It is clear that this approximation might interfere with future pit expansions in new favorable scenarios, but at certain point in time the decision was taken to guarantee the operation feasibility. In such cases, impacts on project's NPV are inevitable and must be deal with caution, evaluating several alternative scenarios to design a strategy to maximize profitability. Relocating waste dumps, stockpiles or mine facilities might be expensive, however it allows pit expansions that will pay for the relocation process and still generate value. The aim of this study is to evaluate, through NPV comparisons considering different scenarios with multiple constraints, the possibility of moving waste piles and infrastructure buildings from their current position and/or defining priorities to after measuring the impact that each constraint represents on the project´s profitability. The methodology will be applied to a phosphate mine, to determine the best alternative from a long-term mine planning perspective.



## KEYWORDS

Mining planning, surface constraints, NPV, ultimate pit.


## INTRODUCTION

Large surface mines represent a great challenge in terms of planning, operation and management. To optimize the entire operation the engineers must deal with several technical aspects and constraints, like orebody modelling, reserves estimation, optimum and operational pit designs, determination of blending necessity, equipment allocation and maintenance, environmental issues among others. Besides these technical aspects, the managing the cash flow and risk during production is a critical part of mining as well as an important part of a strategy to develop new and existing operating mines (Dimitrakopoulos, Martinez & Ramazan, 2007).

The long-term planning engineers consider many of these variables in the early stages of a mining project, therefore decisions involve a high degree of uncertainty of future demands. Moreover, the further the periods are, the greater is the uncertainty (Albach, 1967). In order to obtain the best operational and economic results is important to raise a well-based pit optimization and production scheduling study, given these variables impact on projects´ economics.

The majority of these variables are modified with time in consequence of uncertain prices, unpredictable global markets, and unforeseeable changes in foreign exchange rates, and may jeopardize the operation feasibility (Deutsch, González & Williams, 2015). To deal with them is essential to make many assumptions regarding costs behavior with time. Depending on costs fluctuation, optimum pit may vary altering the total amount of reserves and therefore forcing drastic shifts in production schedule that, according to Ramazan and Dimitrakopoulos (2013), can modify significantly the project´s NPV.

Defining ultimate pit limit is a fundamental problem in mine planning and decisions on this subject will endure to the end of the mine life. According to Cacceta and Hill (2003) ultimate pit limit of a mine is the contour, which is the result from extracting quantities of ore and waste material and reaches the best profitable scenario for operation. As the ultimate pit is based on uncertain parameters and is the reference for the operation to reach the end of the mine life, it affects directly on where infrastructures will be placed to avoid intersecting the pit limits blocking ore and future pit expansions (Deutsch et al., 2015).

Considering the possibility of pit expansion or reduction with time due to the variables mentioned before, engineers must choose surface facilities location with caution once is not easy to relocate these structures. There is always the dilemma between approximating surface facilities to the pit, like the processing plant, waste dumps and tailings dams, to reduce operational costs. It is possible that this approximation might interfere with future pit expansions in new favorable scenarios, but at certain point in time the decision might be taken probably to guarantee the operation feasibility.

The aim of this study is to evaluate, through NPV comparisons considering different scenarios with multiple constraints, the possibility of moving waste dump piles and infrastructure buildings from their current position and/or defining relocation priorities after measuring the impact that each constraint represents on the project´s profitability. The methodology will be applied to a phosphate mine, to determine the best alternative from a long-term mine planning perspective.

## MINE HISTORICAL

According to the Vale Fertilizantes' resources report (Júnior, 2010) the operation started in 1938. Ore composition was mainly by apatite with grades around 20% in a residual material layer. In the end of the 60's, the residual material was depleting and the new source of apatite were the carbonatites found underneath, with mean grade of 5.5%. This forced an update on the process plant, which started to use flotation. At this stage, the apatite was no longer the only relevant mineral, sharing its economic importance with sub products like magnetite and limestone. In 1972, the company built a cement factory to use the limestone tailings with MgO grade below 4.5%, and in 1974 were installed units to produce sulfuric and phosphoric acids.

Many different carbonatites comprise local geology in a cylindrical shape inserted in the waste volcanic rock, called Jacupiranguito. A detailed scale study revealed the occurrence of five different carbonatite intrusions in distinct ages. Currently the ore zone model (phosphate rocks composed by calcite and dolomite carbonatites) contains 14 different lithologies (Figure 1), separated in 5 groups according to their spatial location and mineral similarities. Table 1 shows the relation between grades, lithologies and final products.

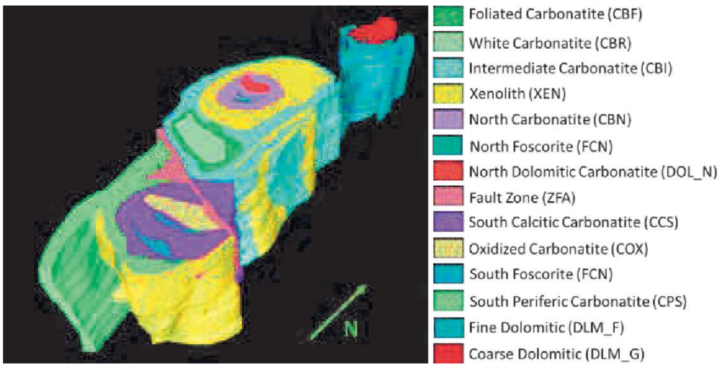


Figure 1 – Ore zone local geology model. Dimensions are 1.13 km (0.70 mi) longitudinal and 0.4 km (0.25 mi) transversal

Table 1 - Ore classification according to cut-off grade and lithology

| Ore Type | Cut-off Grades (%) | | Lithologies | Calcareous Tailings Application |
|---|---|---|---|---|
| | P2O5 | MgO | | |
| A | ≥ 3.00 | ≤ 4.00 | CPS, CCS, FCS, CBI, CBF, CBR, CBN, FCN | Phoscalcium |
| B | ≥ 3.00 | > 4.00 and ≤ 5.00 | CPS, CCS, COX, ZFA, FCS, CBI, CBF, CBR, CBN, FCN | Cement |
| C | ≥ 3.00 | FREE | CPS, CCS, COX, ZFA, FCS, CBI, CBF, CBR, CBN, FCN, DOL_N, XEN, DLM_F, DLM_G | Magnesia |

Currently the pit bottom is located at elevation -140 m (-459.3 ft) and engineers expect to lower to -270 m (-885.8 ft) and probably deeper. The pit is almost entirely developed in fresh and competent rock, which allows a general slope angle around 54°, using benches of 10 m (32.8 ft) and 20 m (65.6 ft) height. Although the ore and waste rocks have good geotechnical parameters, many surrounding surface structures limit pit expansion. There are three waste dump piles blocking the advances to the east, southeast and southwest directions.To the south , there are also the crushing system, homogenization piles and process plant (Figure 2).


Figure 2 - Overall view of the pit location and the surrounding surface structures

To lower vertically the pit bottom it is mandatory to relocate some of these structures. The only horizontal advance direction, which is not blocked by any physical constraint, is to north/northwest, in a region called Mesquita Sampaio where exploration found high MgO grades though.

## METHODOLOGY

The present study aims the evaluation, through NPV analysis, of different scenarios considering several surface facilities and its interference with the mine to find the most profitable alternative for future pit expansions. This will be carried out with a block model containing grades of $P_2O_5$ and MgO (interesting minerals for processing plant) estimated using ordinary kriging, and six constraints (one mining claim limit, three waste piles and two other surrounding infrastructures groups) as shown in Figure 3.

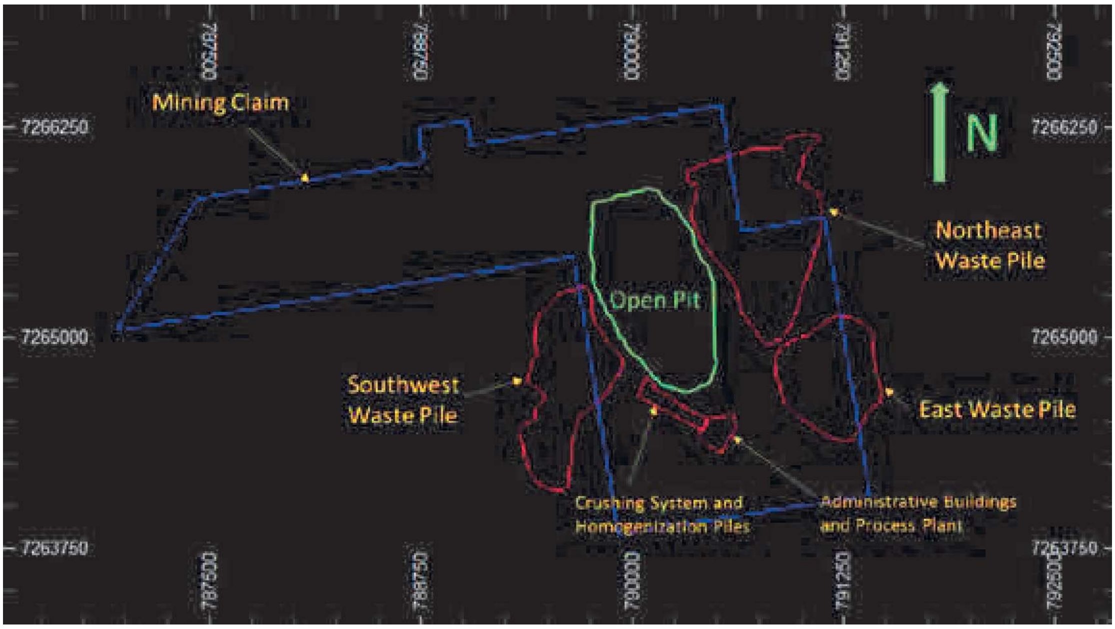


Figure 3 - Location of each constraint considered in this study and the current open pit limit

We considered eight different scenarios in this study, one of them considers to keep mining according current situation (all constraints applied) and another one is the unconstrained scenario to determine the maximum and minimum usage of mineral resources and perform its NPV assessment. Table 2 contains descriptions of all scenarios and some combinations of the six surface constraints (as presented in Figure 3). It is important to say that all scenarios consider the mining claim limit as a hard boundary for every analysis. Having said that, S0 would be the "unconstrained" case to serve as a reference of maximum outcome in terms of mineral resources usage and consequently created the expectation to be converted into ore reserves if the limitations (or constraints) can be overcome.

Table 2 - Constraints combinations considered in each evaluation scenario.

| Scenario | Constraints Considered |
|---|---|
| S0 | Mining Claim |
| S1 | All (current mine situation) |
| S2 | Northeast and east Waste Piles |
| S3 | All Waste Piles |
| S4 | All Waste Piles + Process Plant + Administrative Building |
| S5 | Crushing System + Homogenization Pile + Process Plant + Administrative Building |
| S6 | Southwest Waste Pile |
| S7 | East and Southwest Waste Piles |

For all scenarios were generated optimized pits through Lerchs-Grossmann algorithm, a well-stablished ultimate pit limit problem approach. After that, for the best scenarios, which means the ones that generated the most attractive NPVs, we followed with a mine scheduling to assess, rank and determine the most advantageous scenario.

## RESULTS AND DISCUSSION

The results from the pit optimization are listed in Table 3 and contains NPV, ore tonnes, stripping ratio, pit bottom elevation and average grade for the main minerals considered in this analysis. The NPV results are shown in percentage of a reference case, it was taken the unconstrained scenario (S0) to be the optimistic base case in terms of liberation of all constraints.

Table 3 - Results for ultimate pits containing NPV, Strip Ratio, pit bottom elevation and P2O5 and MgO grades. NPV values normalized to S0 (higher result).

| Scenario | Ore Mass (Mt) | NPV (%) | Stripping Ratio | Pit Bottom Elevation m (ft) | $P_2O_5$ (%) | MgO (%) |
|---|---|---|---|---|---|---|
| S0 | 193.4 | 100.00 | 2.50 | -420 (-1378) | 4.32 | 8.16 |
| S1 | 87.7 | 83.70 | 1.76 | -300 (-984) | 5.31 | 7.66 |
| S2 | 129.7 | 95.90 | 1.91 | -320 (-1050) | 5.34 | 6.69 |
| S3 | 105.0 | 91.40 | 1.78 | -300 (-984) | 5.38 | 7.08 |
| S4 | 105.0 | 91.40 | 1.78 | -300 (-984) | 5.38 | 7.08 |
| S5 | 139.5 | 91.30 | 2.49 | -400 (-1312) | 5.23 | 6.98 |
| S6 | 148.5 | 96.10 | 2.51 | -375 (-1230) | 5.35 | 6.52 |
| S7 | 148.8 | 96.00 | 2.39 | -375 (-1230) | 5.36 | 6.60 |

Figure 4 shows the amount of tonnes and strip ratio. From all eight scenarios, S0 has the highest NPV value and we used it as a reference to normalize the other scenarios results for comparison. S0 also contains the highest total tonnes (waste plus ore), which was expected, given the has only one constraint (mining claim). However, 72% of all contained tonnes are waste material and 12% of this waste is landfill, therefore the relocation costs may lower substantially the NPV for this scenario. Besides, the average grade for apatite contained in ore blocks is the lowest amongst all scenarios.

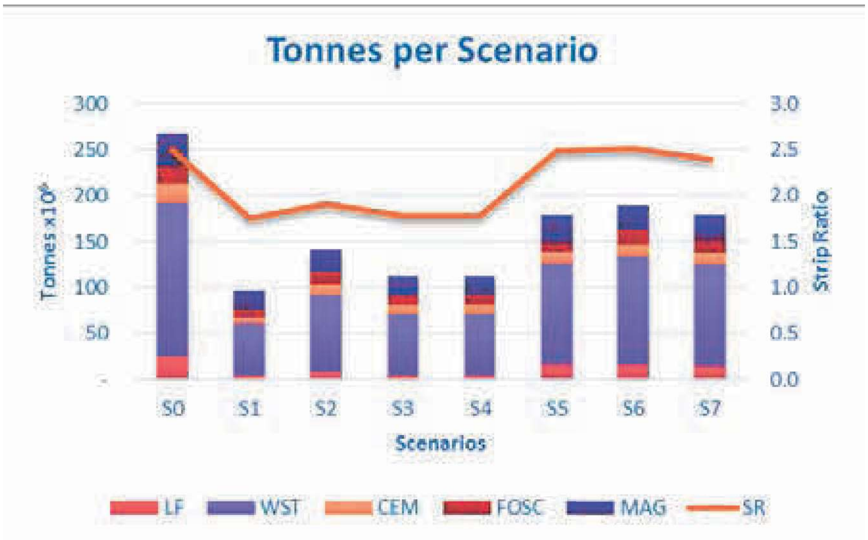


Figure 4 - Total tonnes per scenario and the respective proportion of tonnes of LF (landfill), WST (waste), CEM (cement), FOSC (phoscalcium), MAG (magnesia), SR (strip ratio)

As expected, S1 presented the worst results regarding NPV and total tonnes. This result indicates that surface structures are really blocking significant amount of ore and consequently it reflects on project´s NPV. Ultimate pit bottom is located at elevation -300 m (-984 ft) and, therefore, to deepen the pit it is essential to relocate or unblock some of the surface structures. Even though geotechnical studies demonstrate the local geology is comprised of competent rock making possible to work with 20 m (65.6 ft) bench height and a very steep face angle (75° to 80°), the presence of unmapped joints or fractures, underground water flows, overload around pit walls and other aspects may become a huge concern for pit stability and safety.

S3 and S4 presented the same results. In S3, were kept all waste piles as constraints and disregarded the crushing system, homogenization piles, process plant and administrative building. S4 considers the same situation, just in addition to the waste piles, were kept process plant and administrative building as constraints. The ultimate pit surface for both scenarios are identical and it is possible to conclude that the processing plant and/or administrative building (leaving waste piles as constraints) will not provide any additional profit or increase in reserves. In fact, looking at Figure 5, it can be noticed that the only scenario in which the processing plant and administrative building need to be moved is S0.

Scenarios S6, S7 and S2 presented the best NPV results, respectively, compared to S0. However, it is important to realize that even though S2 presents the lowest NPV it has also the lower stripping ratio among these four scenarios. Is also important to highlight that in all situations is necessary to relocate the crushing system and homogenization piles. The only scenarios where it does not happen are S1 and S5 by definition, where the crushing system is considered as one of the constraints. Figure 5 also shows the crushing system relocation necessity.

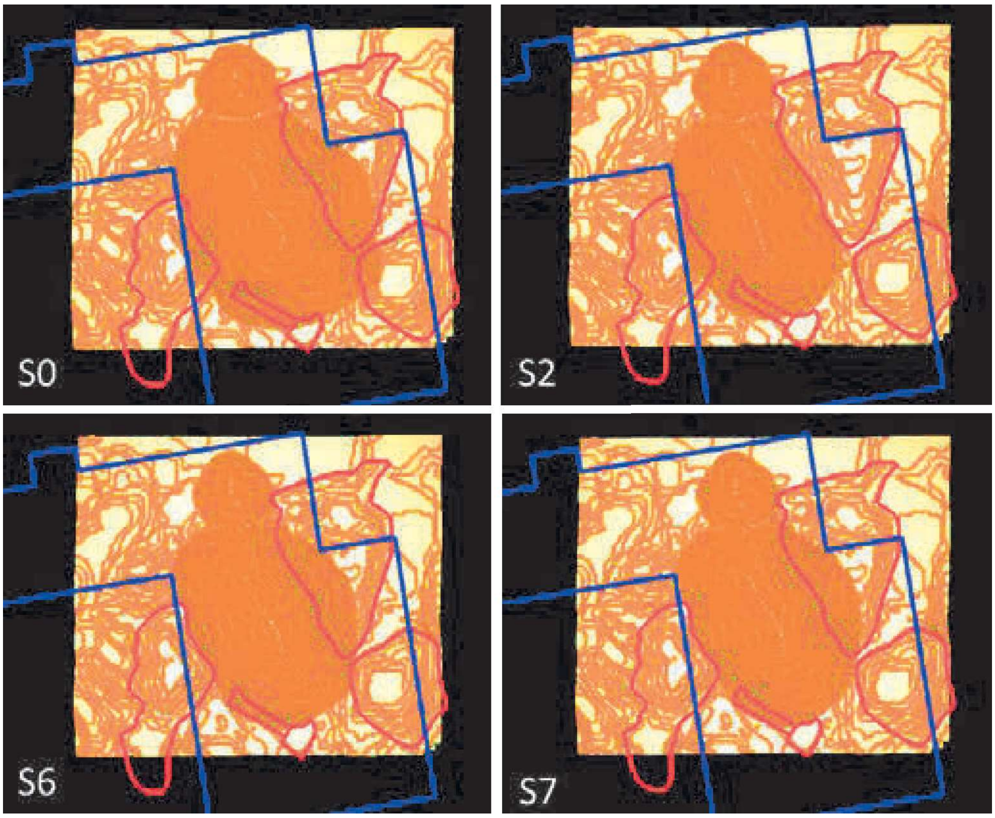


Figure 5 – Visual comparison between footprints of the four selected ultimate pit scenarios and the constraints considered

After choosing these four scenarios, the scheduling process was carried out to verify the resulting ranking from previous analysis. The scheduling was performed according to the mine production necessity and also trying to keep stable the yearly stripping ratio and feed grades. Table 4 shows the results obtained after sequencing the scenarios, along the results from S1 pit for comparison in case no physical constraint is released and consequently no relocation will be done.

Table 4 - Scheduling results for the four best scenarios after scheduling. NPV values are normalized according scenario S0 result

| Scenario | Mine Life (yr) | NPV (%) |
|---|---|---|
| S0 | 38 | 100.0 |
| S1 | 17 | 95.5 |
| S2 | 25 | 107.0 |
| S6 | 29 | 101.1 |
| S7 | 28 | 102.4 |

Scenario S0 turned out to be the worst case after scheduling procedure. Scenarios S6 and S7 switched rank position. The necessity to move east and northeast waste pile in S6 implies relocation of approximately 3.0 Mt more landfill than in S7, causing a reduction on NPV.

Scenario S2 became the most attractive solution at this point. It presented 7% increase NPV compared to S0 and 11.5% when compared with S1 scenario. Despite the total tonnes in the S2 ultimate pit is 20% to 45% less than in S0, S6 and S7, the necessity to relocate landfill and move waste in the first 3 years is 37.5%, 21.7% and 9.4% lesser, respectively. It occurs due to keeping northeast and east waste piles as constraints.

## CONCLUSION

The results presented in this paper show the importance of studying as many alternatives as possible in cases where surface structures are interfering with the pit limit. Some of these surface structures such as east and northeast waste piles demonstrated to be good opportunities to increase the project´s NPV. Moving them increases significantly mineral resources recovery but, in the other hand, the necessity of relocation in the first years penalizes NPV. Other surface structures, like processing plant and administrative buildings, do not seem to be huge constraints as, in various scenarios, pit limits do not intersect them.

Moving crushing system along with homogenization piles and southwest waste pile seems to be the best alternative as demonstrated in this preliminary study. However much of the resources will be left in place and a pit design would be necessary to determine the amount of ore that would be left behind before a decision is taken. In S2 situation, the pit bottom will reach the elevation of -320 m (-1049.8 ft) while the modeled orebody reaches -600 m (-1968.5 ft).

It must be considered in all scenarios the relevance of availability of areas to waste relocation and/or waste removal. As could be seen in Figure 2, the constraints are exactly where they currently are because the juggle to deepen the pit and reducing operational costs. This is a hard constraint and the decision passes through this assessment.

As future developments, geostatistical simulation should be included in further studies to insert grades uncertainty and risk analysis, so better decisions regarding projects profitability could be made. It is also interesting to evaluate the possibility of transition for underground operation, as is not possible to reach some of the resource even in the deepest ultimate pit scenario.

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