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Mine/Mill production planning based on a Geometallurgical Model

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Abstract

The Pau Branco mine supplies two blast furnaces with iron ore lumps, and currently, charcoal consumption for pig iron production accounts for 47% of the blast furnaces' operational cost. A geometallurgical model is presented to support an economic study considering reserve volumes, product quality, and operational costs based on the metallurgical performance of different iron ore typologies. Sample analysis provides values required in the model. From the model, an alternative production plan is presented with a positive impact of USD 25.6M over the current net present value of the mining/mill system.

Keywords: sustainable development, iron ore, tailings, filtering, dry stacking.

1. Introduction

Higher environmental and socio-economic demands in the exploitation of future mineral resources require comprehensive knowledge of ore bodies even in the early stages of the mining process. Geometallurgy combines geological and mineral processing information to create a spatial model for production planning and management.

Geometallurgy is described as an integration of fundamental economic geology and deposit mineralogy into the process of designing successful mine plans and resource recovery schemes (Hoal, 2008). A geometallurgical model can be established with three sub-models: a geological model, a process model, and a production model. The geological model gives quantitative information about minerals, elemental grades, and lithology. The process model must be capable of receiving the information from the geological model and forecasting the metallurgical response for any given geological unit (sample, ore block, or geometallurgical domain). These two models are combined into a production model capable of handling the time frame and different scenarios for ore mining and processing. The production model returns figures such as the amount of final product in a given time, production value, and production costs (Lund *et al*., 2013, Lamberg, 2011).

Applying the geometallurgical concept improves resource efficiency, reduces operational risks, and helps in optimizing production, consequently enhancing sustainability and socio-economic factors (Gomes *et al*., 2015).

This paper describes the development of a geometallurgical model for Pau Branco Mine's iron ore lumps. The model is used to define an alternative production plan, considering impacts on reserve volume, product quality, along with mine and beneficiation operational costs. In addition, the impact on charcoal consumption, which is defined as a function of iron lump quality, and accounts for about 47% of the cost for pig iron production, is evaluated. An economic study on the mine/mill system's net present value (NPV) is also discussed.

2. Materials and methods

Iron ore lumps produced in Pau Branco supply two blast furnaces for seamless tube production at Vallourec, Brazil: Barreiro and Jeceaba. The raw material quality influences the charcoal consumption in these blast furnaces, which accounts for much of the steel production cost. Faleiro *et al*. (2013) developed a statistical model to predict charcoal consumption in blast furnaces based on response surface models and linear regression models. This model estimated charcoal consumption and pig iron production cost as functions of raw material quality, including Fe and contaminant content in the iron ore lumps.

A geometallurgical model for the iron ore lumps of Pau Branco Mine was developed with the aim of maximizing the economic value of the mine/mill system. This model allows adjustment of the mineral process, better control of mine and plant operation, decreases the variability of feed quality, and supports an economic study to define the impact of production plans on the NPV of the mine/mill system.

2.1 Geological model

The first step was to define typologies from the Pau Branco geological model, grouping the geometallurgical units based on geological similarities: goethitic, siliceous, and dolomitic banded iron formations (BIFs), (Gomes *et al*., 2015). Table 1 presents a description of the typologies and their participation in the Pau Branco reserve.

Typology	Description	% Weight in Pau Branco Reserve
Goethitic BIF (T1)	high Fe, presence of martitic hematite, and goethite	5%
Rich Siliceous BIF (T2)	medium Fe, low hydratation, high silica. Presence of martite, hematite, and magnetite	25%
Rich Dolomitic BIF (T3)	medium Fe, high hydratation and clay. Presence of martite, goethite, and hematite	30%
Poor Siliceous BIF (T4)	low Fe, low hydratation and low silica. Presence of matite, hematite, and magnetite	20%
Poor Dolomitic BIF (T5)	low Fe and high hydratation and abundant in clay. Presence of martite, goethite, and hematite	20%

Table 1
Typologies from Pau Branco geological model: poor BIFs represent 40% of the reserve (Gomes *et al*., 2015).

For each typology, 06 samples of 33 kg were collected from different locations inside the mine pit, chosen based in geological data, aiming to be representative in terms of metallurgical response. Each sample was homogenized, quartered, and submitted for chemical, and mineralogical characterization (3 kg), and metallurgical tests (30 kg). Figure 1 shows some of the benches from where typologies were taken: goethitic BIFs (T1), rich siliceous BIFs (T2), rich dolomitic BIFs (T3), poor siliceous BIFs (T4), and poor dolomitic BIFs (T5).

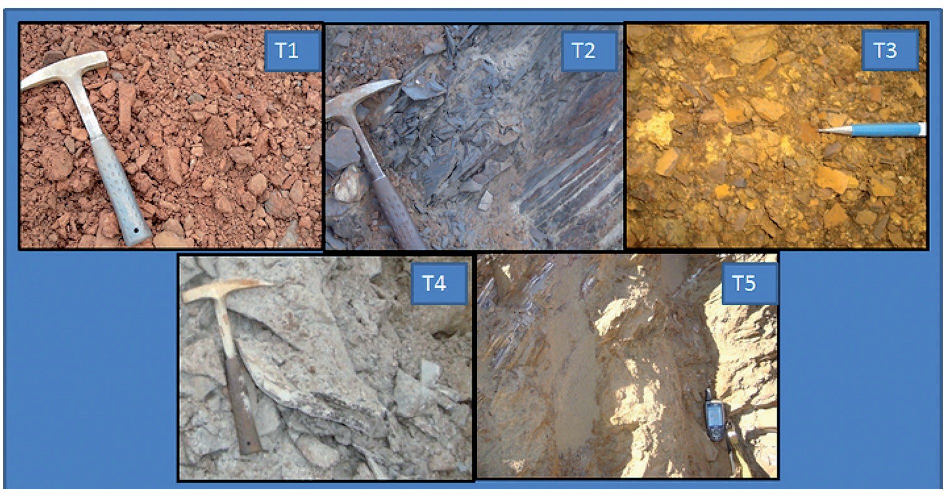

Figure 1
Typologies from Pau Branco mine. For each typology, 6 samples were collected to perform laboratory scale tests.

Chemical analyses of the samples were performed at the Vallourec chemical laboratory. The method utilized for chemical composition analysis was X-ray fluorescence (XRF). Multi-element analysis of iron ore lumps provided overall concentrations of the main constituents (Gomes *et al*., 2015). Mineral identification was done by point counting using reflected-light microscopy. Figure 2 shows photomicrographs of the typologies, and the minerals present in the samples are compiled in Table 2. The chemical analysis of the different typologies is described in Table 3.

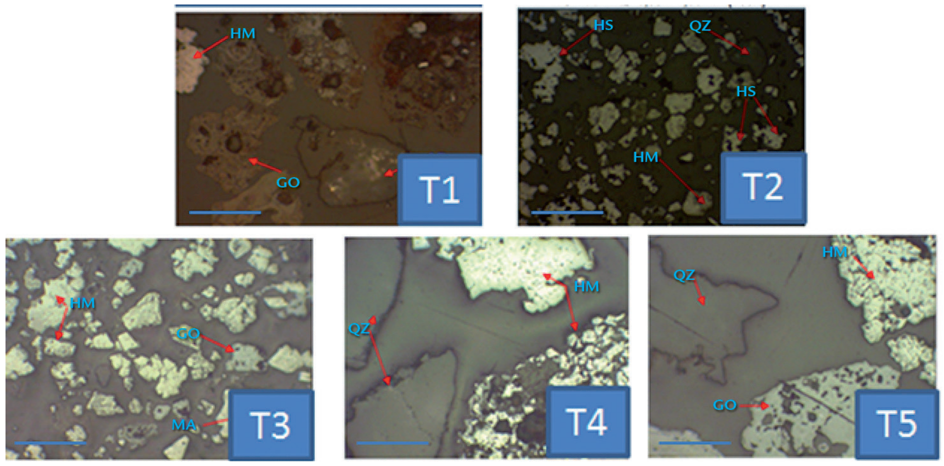

Figure 2
Photomicrograph showing minerals present in the different typologies. hematite (HS and HM), magnetite (MG), goethite (GO), quartz (QZ). Bar Scale 0.2 mm

Table 2
Mineralogical semi-quantitative analyses, defined by optical microscopy. The numbers represent the percentage in volume of each mineral.

	T1	T2	T3	T4	T5
Hematite	28.71	71.6	56.77	57.32	46.89
Magnetite	1.35	6.24	13.3	5.3	14.27
Goethite	60.02	11.89	23.97	22.3	35.85
Quartz	3.95	9.14	5.66	1.44	2.43
Gypsite	4.44	0.68	0	2.81	0.56

Table 3
Chemical analysis of five typologies.The typologies were defined based on common geological features.

	Chemical Analysis (%)					
	Fe	Mn	SiO_2	Al_2O_3	P	LOI
T1	61.02	0.13	1.81	8.32	0.08	4.72
T2	54.32	0.21	1.71	1.13	0.06	3.34
T3	48.65	0.05	1.82	5.52	0.07	8.72
T4	63.05	0.05	3.65	1.51	0.07	3.68
T5	58.94	0.08	3.37	4.61	0.06	5.49

2.2 Process model

Six samples of each typology, were treated in a laboratory circuit that replicates the industrial plant: a 100 mm gap primary jaw crusher, 32 mm and 16 mm screening, cone secondary crusher for particles with diameter greater than 32 mm, and a log washer for the particles between 16 mm and 32 mm. In log washers, the attrition of the particles promotes liberation and elimination of alumina, silica and other contaminants. These forces are weak compared to comminuting, but strong enough to break unconsolidated conglomerates such as clays or break bonds between grains. Operational variables in laboratory log washer were adjusted to the same values as for the industrial: 12 % inclination, residence time of 180 seconds, 100 rpm, processing water pressure of 0.3 megapascal. The concentration factors (CFs) were defined for each typology and represent the ratio between the ore and processed product qualities. The CFs were introduced to the geometallurgical model. Figure 3 shows the typologies before and after mineral processing in laboratory.

Figure 3
Typologies before and after laboratory metallurgical tests. T1, T3 and T5 presented a significant increase in Fe content, due the elimination of LOI, SiO_2, and Al_2O_3 particles. Bar scale (300 mm).

From January to June/2015, industrial tests were performed to calibrate the model, at least 50 batches for each typology. During a batch, the industrial plant feeding was restricted to a specific typology, and the chemical analysis results for both ore, and product were registered. The expected CF, obtained from the geometallurgical model, considering the typology fed, was compared to the actual CF, obtained from the industrial plant tests. Accordingly, the geometallurgical model was calibrated, and supported a production plan, considering gains and losses in both mine, and blast furnace.

3. Results

The CFs obtained through industrial plant processes were coherent, compared to that obtained in the laboratory, indicating the representativeness of the typology's definition and sampling. Those results are shown in Table 4. After this evaluation, the CFs were adjusted for each of the variables (Fe and contaminants SiO_2, Al_2O_3, and LOI) and the geometallurgical model was calibrated.

		T1	T2	T3	T5	T5	Average
Fe	Laboratory	1.05	1.01	1.04	1.02	1.04	1.03
	Industrial	1.07	1.02	1.05	1.03	1.06	1.04
SiO_2	Laboratory	0.75	0.94	0.62	0.75	0.86	0.8
	Industrial	0.72	0.93	0.61	0.7	0.83	0.77
Al_2O_3	Laboratory	0.47	0.59	0.47	0.58	0.59	0.56
	Industrial	0.43	0.56	0.39	0.57	0.47	0.51
LOI	Laboratory	0.59	0.79	0.9	0.98	0.87	0.87
	Industrial	0.53	0.77	0.8	0.92	0.75	0.81

Table 4
Industrial performance showed consistent CFs compared to laboratory metallurgical tests.

4. Discussion

Because of the good alumina CF obtained by the processing of T1, T3, and T5, an iron content increase was noted in the final product. This improvement is related to the presence of goethite and its associated clays minerals, over which the log washer has a high efficiency; besides this, the high hydration present in these typologies allows the breakage and liberation of both silica and alumina particles. The same can be observed for LOI in T1. Both clay and LOI particles are eliminated by attrition because of their fragility. In contrast, quartz (SiO_2 particles are not fragile enough to be eliminated, and the best CF for silica is observed in T3 owing to the high hydration and consequent fragility of its particles.

4.1 Production planning

Currently, the contributions of typologies T3 and T5 are limited by the specification of the products. Consequently, a part of these typologies' volume is not considered in the economic reserve; if current percentages are maintained, there will be a residual volume of these typologies beyond the useful life of Pau Branco.

Considering the calibrated geometallurgical model, a mine planning was developed, limiting the blend of typologies to a processed lump quality of 1.62% Al_2O_3, i.e., 0.5% higher compared to the current product specification. This specification change allowed increased participation of typologies T3 and T5 in the blend feeding of the industrial plant from 20% and 15% to 24% and 25%, respectively. This allows recovery of extra reserve volume that was not technically feasible before for quality restrictions. Table 5 presents the participation of the typologies composing this mine planning and the expected final product quality based on the geometallurgical model.

Table 5
Mine planning considering the increase of participation of typologies T3 and T5. Values represent the expected quality for the final product.

	T1 (4%)	T2 (23%)	T3 (24%)	T4 (24%)	T5 (25%)	Average
Fe (%)	65.29	55.42	51.09	64.94	62.48	60.62
SiO_2	1.3	15.91	11.16	2.56	2.8	7.67
Al_2O_3	3.58	0.63	2.15	0.87	2.17	1.62
LOI (%)	2.5	2.57	6.98	3.39	4.12	4.31

4.2 Impact on mine/mill system

Iron ore lump quality affects pig iron production operational cost. Diluting the Fe content decreases the productivity of the blast furnaces; consequently, more charcoal is required to produce the same quantity of pig iron. Additionally, silica and LOI are associated with the generation of fines, which decreases the permeability of the charge and the effectiveness of the process. Higher volumes of alumina raise the fusion point of the slag, implying a higher demand for charcoal in order to raise the temperature of the reactor, avoiding cold runs.

Based on the model developed by Faleiro *et al.* (2013), among the evaluated variables, Al_2O_3 is the one that affects pig iron operational cost most. While an increase of 1% of Al_2O_3 in iron ore increases the specific consumption of charcoal by 20 kg/t, the same changes in SiO_2 and LOI levels represent increases of only 0.01 kg/t and 0.16 kg/t, respectively. Conversely, a 1% increase in Fe content decreases the specific charcoal consumption by 4.5 kg/t.

Considering pig iron production of 500 kt per year, an increase of 0.5% Al_2O_3 in iron ore lumps implies 10 kg more charcoal per ton of pig iron produced. This accounts for a production cost increase of USD 1 M per year, or an NPV of USD -4.1M in 10 years with a discount factor of 12%. Conversely, the same change in product quality increases the reserve of iron ore lumps by 15%. This gain in reserve represents an NPV of USD 30M considering the same time horizon and a margin contribution of 30 USD/t for iron ore lumps. Table 6 presents a comparison between the two alternatives.

Table 6
Comparison between two alternatives for iron ore processed lump quality.

		Fe	SiO_2	Al_2O_3	LOI	NPV Impact (USDM)
Base Case	Feeding	56.84	10.49	2.72	4.87	0
	Processed ore	58.17	8.25	1.12	3.96	
Scenario 01	Feeding	56.83	10.71	3.56	5.44	25.6
	Processed ore	60.62	7.66	1.62	4.31	

5. Conclusions

Geometallurgical modeling of iron ore lumps was applied to the Pau Branco Mine reserve. Samples of the typologies present in the Pau Branco Mine were collected, characterized, and submitted to metallurgical tests in order to define the behavior of the ore through beneficiation treatment in an industrial plant. Concentration coefficients were determined and introduced into the geometallurgical model. A mine plan was developed considering an increase of 0.5% Al_2O_3 in iron ore lumps compared to the current quality.

The impact on pig iron production operational cost due to this change was calculated using a model developed by Faleiro *et al.* (2013), and a negative NPV impact of USD 4.4M was estimated. Despite this, the gain in iron ore lump reserve and reduction of mine operational costs summed to an overall positive impact of USD 25.6M in the NPV, indicating the feasibility of the production plan for the mine/mill system.

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