International Journal of
Georesources and Environment
http://ijge.camdemia.ca, ijge@camdemia.ca
IJGE 2018 **4(1)**: 9-13
Available at http://ojs.library.dal.ca/ijge
Section – Mineral Resources Extraction

Optimization for Production and Processing of Low Grade Iron Ores

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Abstract: The purpose of this paper is to maximize the utilization of low grade iron ores. The production technology of iron ores in Anqian Mining Company was introduced and the ore mass distribution in different production location was analyzed firstly. The processibility indexes for different grade ore, such as grinding time, concentrate grade and the concentrate yield were obtained in the laboratory magnetic tube tests. On the basis of digital ore deposit model which integrates ore natural attributes with processing attributes, the ore blending optimization model containing two stages were established using big M simplex algorithm. The first stage model is to minimize the ore transportation cost under the restriction of output ore grade and pit production conditions. At the second stage, a system optimization model aims at the furthest use of resources. This model meets not only the production constraints of mining and processing field, but also ore beneficiability and the system output requirements of the concentrate ore grade.

Keywords: low grade iron ore, processibility indexes, transportation work, concentrate control, big M algorithm, ore blending model

1 Introduction

China is the biggest market of iron ores consumption. However, most iron ore deposits in China have the low-grade, complex-type, weak magnetic and refractory features. Under the current economic and technical conditions, effective utilization of low-grade and refractory iron ores is the urgent problem to be solved. This is important to improve the utilization rate of mineral resources and attain the goal of sustainable development in mining (Lei 2011).

In this paper, raw ore quality and different grade of ore processibility in Anqian Mining Company were analyzed. Ore blending optimization model in mining pit and processing plant were developed to achieve the maximum utilization of low-grade refractory ores under the economical and production conditions. This will ensure the stable operation of the mining company, and maximize the production life, therefore, maximize the economic and social benefits in the life cycle.

2 Production Background of Anqian Mining Company

As a mining joint venture, Anqian Mining Company has stripping and mining capacity of 40 million tons ores totally, including 14 million tons of iron ore, the raw ore processing capacity of 8.34 million tons. By the end of 2011, the geological reserve of iron ore had 1.18 billion tons and the amount of ore in open pit was 0.21 billion tons. The main ore type is hematite, which is classified into industrial grade ore and low-grade ore according to the industrial indexes. The disclosed grade is 24.5%. There are 3 production locations, Xu Dong Gou, Dumb Ling, and West Back (Figure 1). Ore is transported and processed by truck-crushing-tape system (production location – stationary crushing station – feeder – belt conveyor – Anqian dressing factory warehouse). The company has a total of two sets of tape system. Xu Dong Gou production location has an independent tape system, dumb Ling and West Back production location share the other one. The mineral processing adopts three-stage crushing with single closed circuit, stage grinding, coarse separation, gravity separation-strong magnetic-anionic reverse flotation. The sketch of distribution and transportation of production locations is shown in Figure 1.

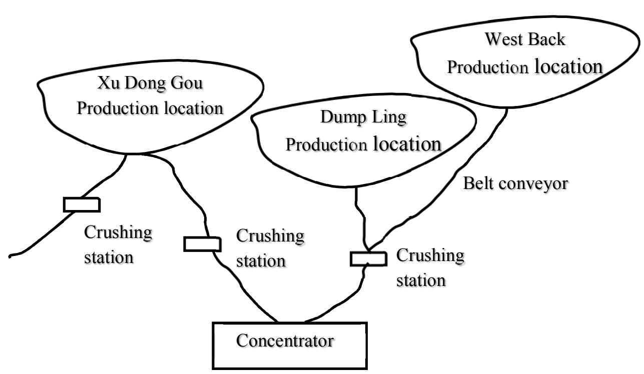

Figure 1. A sketch of product distribution and transportation locations

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DOI: 10.15273/ijge.2018.01.002

3 Quality and Processibility of Iron Ores

Anqian Mining Company provides most of the ores to the concentrating mill for iron concentrate production and sells another part of the ores to Qidashan Dressing Plant. The main recovery element of iron ore is iron, and the content of accompanying elements does not reach the standard of comprehensive recovery. Though the harmful ingredients of sulfur and phosphorus are not high, so the content of silicon dioxide. Based on the mineral composition of the iron ores in Anqian district, they can be divided into three types, hematite quartzite, magnetite quartzite and false hematite quartzite. Hematite quartzite has the color of steel-like grey, brownish grey and grey red with thin banded structure. It is distributed on the surface and shallow seams. Most of the magnetite quartzite is distributed in deep seams. False hematite quartzite has thin banded and fake-like structure, which accounts for a smaller proportion of iron ores in this area (Li 2012).

Blending optimization not only requires the optimization in the mining process, but also has to satisfy the requirements of concentrator processing capacity, mine production and grade control, to realize the stable output of iron concentrate with constant rate of production and expected grade. Therefore, the ore processiblity of different location needs to be studied and to apply the processiblity index to the blending model. According to the statistical data from ore dressing experiments in Anqian Mining Company (Qiu 2009), there is a relationship among the grinding time, the sorting index, hourly throughput per ball mill, the comprehensive concentrate grade and the comprehensive tailings grade index (Wang 2016). When the grinding time is less than 20 minutes, the concentrate grade can reach 58% and concentrate yield reach 15%. Hence ore dressing plan can be realized: hourly throughput per ball mill is 248 t/h, the comprehensive concentrate grade is 7.5%, and the grade of comprehensive tailings is 10.2%. When the ore is mined from different production location, the blending ore processibility indexes in the test can be calculated by the following equations:

Grinding time: $t = \sum (t_i p_i)$ (1)

Comprehensive concentrate grade: $\beta = \sum (\beta_i p_i)$ (2)

Concentrate yield: $r = \sum (r_i p_i)$ (3)

where i stands for different mining area, p is the proportion of ore. In order to ensure the qualified grade of concentrate, the ore which has grade of concentrate less than 54% in separation test should be strictly controlled and cannot exceed the limit of 5%. Through the indoor magnetic tube test, the separability of different grade ore was analyzed. The grinding time, the concentrate grade and the concentrate yield were measured. The results are listed in Table 1.

Table 1 The processibility indexes of raw ore

No.	The grade of raw ore %	Grinding time /min	Fine ore grade %	Fine ore yield %	Hourly throughput per mill t/h	Concentrate grade %	Tailings grade %
1	22-24	15-20	59-61	15-20	240-250	67.5	10-10.5
2	22-26	20-25	58-60	20-25	230-240	67.5	10-10.3
3	22-26	20-25	56-58	20-25	220-230	67-67.5	10-10.5
4	24-26	26-28	52-54	25-30	220-230	66-66.5	11-12
5	24-28	20-25	58-60	25-30	230-240	67.5	9.8-10.2
6	26-30	15-20	59-61	30-35	240-250	67.5-68	9.2-9.6
7	26-30	15-20	59-61	35-40	235-245	67.5-68	8.8-9.2

4 Ore Blending Optimization Model

4.1 Transportation work minimization model

(1) Objective function

According to the actual situation of the mine, a total of three mines is considered in ore blending at the same time (Pan 2016). It is assumed that there are i blasting piles waiting to be mined in ore blending, the distance from the *ith* blasted muck pile to the crushing station is l_i, In $m \in [0,1]$, m indicates whether to choose this mine, 1 means "selected", and 0 means "not selected". Assumed that the amount of ore to be mined from the *ith* muck-pile is x_i, the transportation work is W, the goal of mining is to achieve the minimum transport power under the premise of meeting the target grade. The total mineral occurrences are 54. The objective function is expressed as:

$$W_{\min} = \sum_{i=1}^{54} m x_i l_i \quad (4)$$

(2) Constraint of ore quantity of each muck-pile

Due to the limitation of the maximum production capacity of electric shovel c_s, the maximum amount of digging from each pile could not be more than the maximum production capacity of electric shovel, the blasting pile used in blending model must ensure mine output.

$$mx_i \geq 0 \quad (i = 1, 2, 3, \ldots, 54) \tag{5}$$

$$x_i \leq c_{\mathrm{s}} \quad (i = 1, 2, 3, \ldots, 54) \tag{6}$$

(3) Constraint of the total output of each pit

Taking into account the requirements of advance mining of open pit and mining continuity, the total amount of ore mined in each pit cannot exceed the maximum limit of exploitation of the pit and not be less than the minimum limit of exploitation. n = 1, 2 and 3 stands for Xu Donggou, Mute ridge, and West big dumb, respectively. Their specific constraints are as follows:

$$m_n \leq \sum_{i=1}^{18} mx_i \leq M_n \quad n = 1, i = 1, 2, 3, \ldots, 18 \tag{7}$$

$$m_n \leq \sum_{i=19}^{36} mx_i \leq M_n \quad n = 2, i = 19, 20, 21, \ldots, 36 \tag{8}$$

$$m_n \leq \sum_{i=37}^{54} mx_i \leq M_n \quad n = 3, i = 37, 38, 39, \ldots, 54 \tag{9}$$

(4) Constraint of target grade

It is assumed that the total iron and ferrous iron target grade of each crushing station are respectively e_n and p_n, the total iron grade for each blasting pile to be mined is a_i, ferrous iron grade is f_i, and the three crushing stations are marked with 1, 2, 3, the specific constraint expressions are as follows:

$$\sum_{i=1}^{18} ma_i x_i = e_1 \sum_{i=1}^{18} mx_i$$
$$\sum_{i=1}^{18} mf_i x_i = p_1 \sum_{i=1}^{18} mx_i \quad n = 1, i = 1, 2, 3, \ldots, 18 \tag{10}$$

$$\sum_{i=19}^{36} ma_i x_i = e_2 \sum_{i=19}^{36} mx_i$$
$$\sum_{i=19}^{36} mf_i x_i = p_2 \sum_{i=19}^{36} mx_i \quad n = 2, i = 19, 20, 21, \ldots, 36 \tag{11}$$

$$\sum_{i=37}^{54} ma_i x_i = e_3 \sum_{i=37}^{54} mx_i$$
$$\sum_{i=37}^{54} mf_i x_i = p_3 \sum_{i=37}^{54} mx_i \quad n = 3, i = 37, 38, 39, \ldots, 54 \tag{12}$$

(5) Constraints of magnetic rate

In order to ensure the balance of total iron and ferrous iron during ore blending, magnetic rate needs to be restricted. a_i is used to express the total iron grade, and f_i is used to express the grade of ferrous iron. The specific expression is as follows:

$$\frac{a_i}{f_i} \geq 18 \quad i = 1, 2, 3, \ldots, 54 \tag{13}$$

4.2 Concentrate control model

The optimal blending model of minimizing transportation work is suitable for mines with little difference in selectivity. For the mining-beneficiation combined enterprise like Anqian Company, the final goal of blending optimization is to maximize the profit in the whole life cycle of mine, or to maximize the available resources utilization by economic way.

(1) Objective function

The objective function is to maximize the total concentrate output.

$$P_{\max} = S \sum Q_i r_i - \sum Q_i (d_i + g_i) \tag{14}$$

Constraint conditions:

$$Q = \sum Q_i \tag{15}$$

$$Q_i \leq M_i \tag{16}$$

$$\beta = \frac{\sum \beta_i Q_i r_i}{\sum Q_i r_i} \geq 58\% \tag{17}$$

$$d_i = \lambda_d F_1(l_i) \tag{18}$$

$$g_i = \lambda_g F_2(t_i) \tag{19}$$

$$T = \sum t_i p_i \leq 20 \tag{20}$$

$$\text{When } \beta \leq 54\%, \text{ then } \frac{Q_i}{Q} \leq 5\% \tag{21}$$

In the above formulae, P – the whole profit; d_i – mining cost; g_i – processing cost; λ_d, λ_g – adjust indexes for mining and processing cost; F_1, F_2 – functions for mining and processing cost; M_i – the amount of ore which can be mined; r_i – concentrate yield; Q_i – raw ore production; Q – the total amount of raw ore mining; β – concentrate grade; S – price coefficient; T – comprehensive grinding time; and t_i – grinding time.

5 Algorithm Analysis and Implementation

Resource allocation optimization about coordinated mining of multiple mining areas in open pit mine is a linear programming problem. But the model does not fully conform to the standard of simplex method, because of the specific constraints and other reasons. So simplex big M method is well suitable for solving this type of problem.

5.1 Big M method

The large M rule is to construct an auxiliary linear programming problem by adding some artificial variables to the original constraint equation as dummy variables (Xiong 2014). It is obvious that there is a basic feasible solution to this planning problem. Dummy variables are used to replace the base variables. For this purpose, a very large positive M is introduced to control the value of artificial variables (Xiong 2104). Then the standard objective function of the simplex big M method can be described as follows:

$$F_{\max} = \sum c_j x_j - M \sum x_j \tag{23}$$

where x_j is artificial variable. c_j is the price coefficient, M is the coefficient of the artificial variables. Because M is a very large number, so only when $x_j = 0$, F can get the maximum value. At the same time, the introduction of the artificial variable has no effect on the solution of the original problem.

5.2 Calculation steps of big M method

(1) Convert concentrate control model to the standard form of simplex method, and introduce artificial variables, to construct the unit matrix;
(2) Find an initial basic feasible solution;
(3) Determine whether the basic feasible solution is the optimal solution, inspection criteria are as follows:

The test number $\partial_j = c_i - c_B{}^{-1} p_j$ corresponding to the non-base variable x_j, which is less than or equal to 0; c_i is the coefficients of base variable; c_B is the coefficient of non-base variable; p_j is the constraint coefficient of non-base variable;

If all $\partial_j \le 0$, stop calculation, the optimal solution is obtained, otherwise turn to step (4);
(4) Iteration (find the next feasible solution)

The purpose is to search for a base variable, namely a non-base variable is transformed into a base variable.

The principle of selection is to find the maximum number in all tests:

$$\max\{\partial_j \mid \partial_j > 0\} = \partial_k \tag{24}$$

Then x_k is converted from a non-base variable to a base variable.

Since there is a non-base variable into a base variable, there is a base variable that becomes a non-base variable as well, which is called the out-of-base variables. Selection principle is:

$$\min\left\{\frac{b_i}{a_{ik}} \mid a_{ik} > 0\right\} = \frac{b_l}{a_{lk}} \tag{25}$$

Then, the original *ith* base variable is transformed into a non-base variable, and the base matrix and the non-base matrix are updated. a_{lk} is the principal element, that is, in the process of searching for the next feasible solution, the row of a_{lk} located in the matrix should be considered first, and find the constraint equation. By means of the coefficient transformation, a new basic feasible solution is obtained by constructing a unit matrix with other row coefficients, and then jump back to step (3).

According to the above algorithm steps, the algorithm flow chart is demonstrated in Figure 2.

6 Conclusions

According to Anqian Mining Company production process, the ore quality was discussed. Through the indoor magnetic tube test, the processibility of different grade ore was analyzed. The grinding time, the concentrate grade and the concentrate yield were measured. On the basis of established digital geological model of the deposit, two-stage blending optimization models were established. In the first stage of the model, the target is the ore transportation work minimization meanwhile meeting the conditions of the grade of raw ore output and pit production. The second stage was a system optimal model, the target is to maximize the profit of the company, at the same time, the production process constraints of mining and dressing, requirements for ore beneficiablity and grade of concentrate should be satisfied. In this paper, the nonlinear solution of the model and its realization in production were analyzed and proposed. The method has been applied to Anqian Mining Company successfully.

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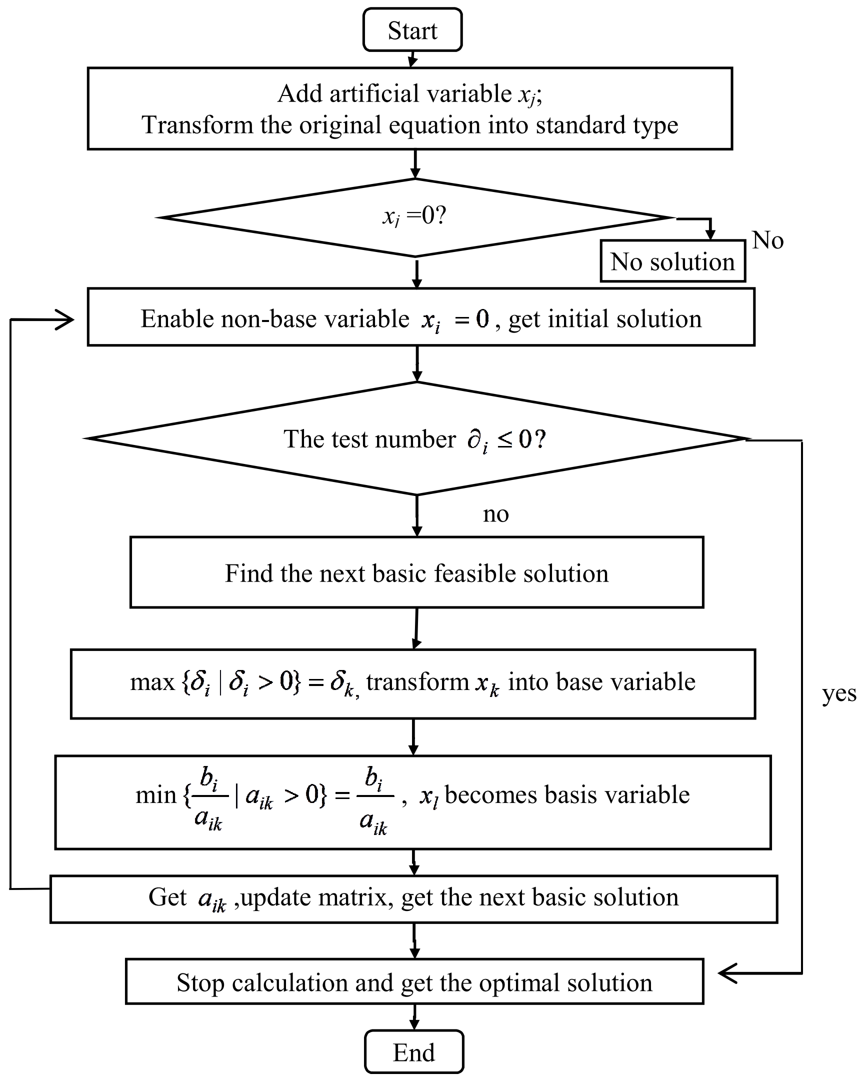

Figure 2. Flow chart of resource allocation optimization algorithm