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Original Article

Combination of gravity concentration variables to increase the productivity of the Brucutu mineral processing plant

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ABSTRACT

The jigging process is one of the oldest ways used to concentrate ores in the world, suitable for small and medium-sized employability, and is composed of a pre-concentration step as a way to reduce costs. Within this perspective, a test campaign for laboratorial mineral concentration was set up, in order to determine the main variables (and their interactions) that may have an influence on the concentration of iron ore from the Quadrilátero Ferrífero by the jigging process. A factorial planning was prepared so that an accurate statistical analysis of experiments could be performed. A combination of the three variables were studied (feed granulometry, background layer, and bed mass) promoted an iron recovery equal to 73.14%, a distribution of silica of 89.05% on the tailing and a selectivity index of 3.80. Thus, the methodology enabled a useful statistical evaluation and can contribute to decision-making regarding the parameters of interest in the jigging process.

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1. Introduction

1.1. Gravity concentration

The Quadrilátero Ferrífero, located in the central region of Minas Gerais, is one of the most important Brazil's mining regions, source of massive gold, imperial topaz, bauxite,

manganese and iron deposits. The latter has become the symbol of the State's primary activity.

The current iron ore scenario presents various challenges with several reserves close to being depleted forcing the maximum use of the current processing plants [1]. Including the gravitational concentration.

Gravity concentration is a mineral separation method applied to particles of different densities in the mixture. As a

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separation mechanism, most gravity concentration processes use the fall resistance offered by the medium that has the properties of a fluid (usually water, a dense liquid or mixture of liquid and solid particles held in suspension) [2].

Jigging is one of the industrial gravity concentration processes available. A jig operates in a cyclic manner where one cycle consists of four stages, namely, inlet, expansion, exhaust, and compression [3].

The result of this process is a stratification of the bed, which corresponds to the particle separation in layers with densities increasing from the top to the base [4].

The choice of an appropriate physical method for the concentration of a mineral depends on: the liberation size, an effective difference in some physical properties that permit the separation, the volume of ore to be processed, as well as the feed and product contents.

According to [5], the methods of gravity concentration declined in importance in the first half of the last century due to the development of the flotation process, which allows the selective treatment of complex low content-ores. Nowadays the main iron ore processing plants in Brazil operate through reverse cationic flotation [6]. However, it has remained as the principal preconcentrating method for iron and tungsten ores and is widely used for the treatment of coal and tin ores.

This article has the goal of performing a test campaign of mineral concentration in a laboratory, using a DECO[®] jig, model A-173-A, in order to meet the main variables (and their interactions) that may influence the concentration of iron ore from the Quadrilátero Ferrífero. A factorial planning was prepared, in order to perform an accurate statistical analysis of experiments.

1.2. The statistical planning applied to experiments

According to [7], in the special case of mineral processing, data generated in experiments are basic parameters both for implementing new routes as well as adjusting and optimizing the existing routes.

Experimentation is a vital part of a scientific method. Certainly there are situations where the scientific phenomena are so well known that results can be achieved using mathematical models, which can be developed directly by the application of physical principles. The models whose phenomenon follow directly a physical mechanism are called mechanistic models. However, complex systems, such as mineral processing, generally make decisions based on empirical models.

1.3. Yates algorithm in factorial design

A 2^k factorial design is one in which k variables or factors labeled A, B, C, D, ... are each allocated to two levels, conventionally ± 1 in coded coordinates, and every possible combination of the \pm sign is run, typically in a completely randomized or randomized block order. A fractional two-level design is one that employs only a fraction of the 2^k runs. Such designs use a 2^{-p} fraction of the whole 2^k runs and, therefore, have been designated 2^{k-p} fractional factorials. The two level factorial designs have mainly been used in full and fractional form [8,9]. A large compilation of 2^{k-p} designs was made available by the [10,11] *apud* [9]. See also [12] and [13]. Yates' algorithm to estimate the effects and also the reversed form to estimate the residuals in a 2^k factorial design are well known. We develop a modification of these two algorithms and call them the modified Yates' algorithm and its inverse. We show that the intermediate steps in our algorithm have a direct interpretation as estimated level specific mean values and effects. Further, we show how Yates' or our modified algorithm can be used to construct the blocks in a 2^k factorial design and to generate the layout sheet of a 2^{k-p} fractional factorial design and the confounding pattern in such a design. In a Final example we put together all these methods by generating and analyzing a 2^{6-2} design with 2 blocks. This paper demonstrates the use of an algorithm for the analysis of effects and residuals for full and fractional factorials. The same algorithm can be used for selecting fractions and blocks, and for observing aliasing patterns from factorial layouts.

1.4. Brucutu Plant – Vale S.A

Table 1 shows the type of products, concentration and step your percentage corresponding to the best campaign ever recorded. According to this table, it can be noted that the jigging was responsible for 24% of the annual production of the concentration plant.

2. Methods

The samples for studies were supplied by the company Vale S.A, where chemical analyses were also carried out.

A total of 94.54 kg were placed in six plastic bags and transported to the laboratory of mineral processing in the Instituto Federal de Minas Gerais (IFMG), for sample preparation.

Factorial planning was chosen as a tool for studying the ore behavior in terms of variation of particle size of jig's feed, the

Table 1 – Data of the Brucutu concentration plant.

Product	Step	Production	
		%	10 ⁶ t
Sinter feed (SF1)	Jigging	24	5.7
Sinter feed (SF2)	Low intensity magnetic separator	5	1.3
Sinter feed (SF3)	High intensity magnetic separator	10	2.5
Pellet feed (PF)	Flotation	60	14.4
Total		100	24.0

Table 2 – Variables selected for factorial planning.

Variables		Levels	
A	Feed granulometry	Fine (-)	Coarse (+)
B	Background layer	Pebbles (-)	Steel balls (+)
C	Bed mass	250 g (-)	300 g (+)

type of pebbles that make up the bed, as well as the amount of mass that forms the pebble bed.

2.1. Ore sample and hematite pebbles preparation

For sample homogenization, a large conical pile was formed, from which all material was collected and a new conical pile was formed. This procedure was repeated 10 times to ensure complete homogenization of material. Finally, the last pile was divided into two volumes, and two size fractions ($-3.35 + 1$ mm and $-2.36 + 1$ mm) of each mineral sample were obtained using screens. All material below 1 mm was rejected.

To manufacture of hematite pebbles, material used to compose the background layer of the bed, compact hematite samples were also taken from the Brucutu mine. After being crushed, all material was sifted to a range of $-19.0 + 12.0$ mm and placed in a steel ball (40 mm of diameter) mill for 2.5 h for reduction of the mineral particle edges. Finally, the whole volume was classified between $-12.7 + 9.52$ mm, for elimination of the finer fractions generated. Thus, it was possible to produced pebbles with the proper size and shape for jig's bed.

2.2. Jig concentration

The DECO[®] jig, A-173-A, with cross section dimensions 203×305 mm, using a fixed sieve, and pulsating the water (to provide the movement) was the equipment used in the bench tests proposed. For conducting such tests the jig operated with a 260 mm of displacement, frequency of 150 strokes per minute and wash water flow rate of 9.33 l per minute.

In order to reach the optimal conditions for concentration of the itabirite ore, three variables were selected: feed granulometry, background layer and the bed mass.

The range of particle size processed by jigs depends on the type of material as well as the equipment features. The material at first was divided into two different size ranges. The first, between 2.36 and 1 mm, called the fine range. The second, between 3.35 and 1 mm, being specified as coarse range. In

this form the granulometry was defined as one variable called "A".

Another variable is the background layer consisting of two different materials. Two bench tests were executed, being some with steel balls and others with hematite pebbles. The background layer is the second variable named "B".

Finally, another variable to be studied was the mass of pebbles that formed the jig's bed, i.e., the mass of the bed that would define the numbers of layers at the bottom of the jig. This was taken as variable "C". Therefore, the concentration of hematite was in function of the three variables. Table 2 shows the variables selected for the study and their respective levels for analysis.

To work these values, the factorial planning was used on two levels while considering the three variables, which generated eight tests. For the experimental error evaluation, replicas of these experiments, generating sixteen tests. The planning of experiments is presented in Table 3 with the values used in each test. The sequence of execution of testing was random and followed the order presented.

As responses, analyzed were the interactions between variables, the iron recovery and the selectivity index.

3. Results and discussion

3.1. Granulometric analysis

The granulometric analysis of the original sample from Brucutu presented about 73.41% of the material was between 3.35 and 1 mm while on the other hand 45.12% was between 2.36 and 1 mm.

3.2. Analysis of technological experiment by the factorial planning

A statistical analysis of experimental results obtained by employing the factorial planning with responses that affect

Table 3 – Factorial planning.

Test	Variable	Sequence	Variable			Variable		
			A Feed granulometry	B Background layers	C Bed mass	A Feed granulometry	B Background layers	C Bed mass
1	T	8°	-	-	-	<2.36	Hematite	250
2	A	7°	+	-	-	<3.35	Hematite	250
3	B	4°	-	+	-	<2.36	Steel	250
4	AB	3°	+	+	-	<3.35	Steel	250
5	C	6°	-	-	+	<2.36	Hematite	300
6	AC	5°	+	-	+	<3.35	Hematite	300
7	BC	2°	-	+	+	<2.36	Steel	300
8	ABC	1°	+	+	+	<3.35	Steel	300

Table 4 – Results obtained using the factorial method (iron recovery).

Experiment	R1	R2	Y – 1	Y – 2	Y – 3	AD	Effect	R1 – R2	(R1 – R2) ²	Tcal	^a Sig.
1	73.14	66.47	203.2	413.7	771.5	96.44	T	6.7	44.49	–	–
2	35.67	27.91	210.5	357.8	–280.9	–35.11	A	7.8	60.21	13.35	Yes
3	66.83	70.32	185.6	–139.8	–6.2	–0.77	B	–3.5	12.16	0.29	No
4	41.35	31.99	172.2	–141.0	–29.5	–3.69	AB	9.4	87.67	1.41	No
5	56.92	60.71	–76.0	7.3	–55.9	–6.99	C	–3.8	14.39	2.66	Yes
6	36.43	31.58	–63.8	–13.5	–1.2	–0.15	AC	4.8	23.48	0.06	No
7	60.74	71.05	–49.6	12.2	–20.8	–2.60	BC	–10.3	106.27	0.99	No
8	15.35	25.04	–91.4	–41.8	–54.0	–6.75	ABC	–9.7	93.83	2.57	Yes

R1; R2 are responses (iron recovery); T, reference.

Y – 2; Y – 2; Y – 3 are variables.

AD, average difference; Tcal, statistical significance calculated; Sig., significance.

^a Significance occurs when $Tcal > 2.31 (Tstd)$; Tstd, standardized statistical sig.

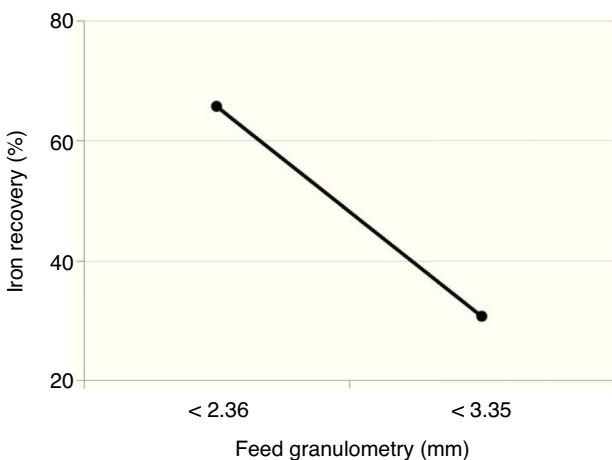
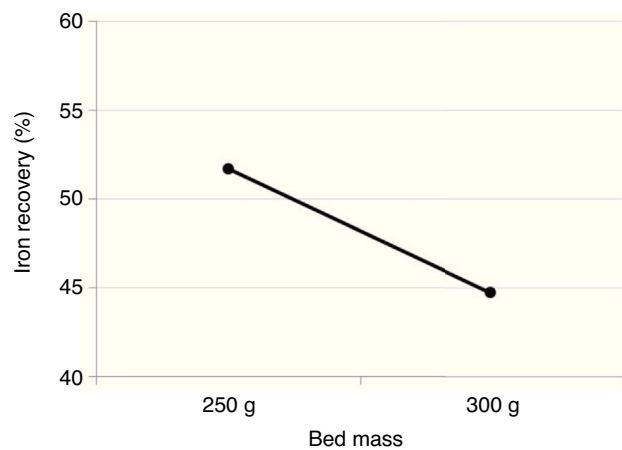
the iron recovery, silica in the tailing, and the selectivity index was made using the EXCEL[®] Software. The analyses of the influence of variables and their interactions on the experimental response were carried out based on Yates' Factorial Method.

3.3. Analysis of iron recovery

According to the results presented in Table 4 the factors that had more significance with respect to iron recovery were the variables A and C. According to [14], the size plays a role in particle stratification during fluidization, and they observed that in a liquid-particle fluidized column, binary mixtures of smaller size heavy particles and larger size light particles would show normal stratification at lower fluid velocity.

Also, the conclusions of the work of [15] reveal that the effectiveness of the separation was greatly influenced by the operating variables of the jig and the particle size of the ore. It was possible to conclude from Table 4 that the factors A and C, when applied isolated, can be more meaningful, while when they work together, they cannot produce good results. But the ABC association was significant. These interactions presented a $Tcal = Tstd > 1.86$.

In Figs. 1–3 are presented the variations of iron recovery in concentrate, as a function of each variable and its main effects on iron recovery. From this it is stated that:

**Fig. 1 – Iron recovery versus feed granulometry.****Fig. 2 – Iron recovery versus types of pebbles.**

- considering the feed granulometry from the lower level to the upper, this was the variable that most contributed negatively to iron recovery;
- the exchange of the material for the bed did not produce significant variation;
- the increase in the mass of the bed was also unfavorable.

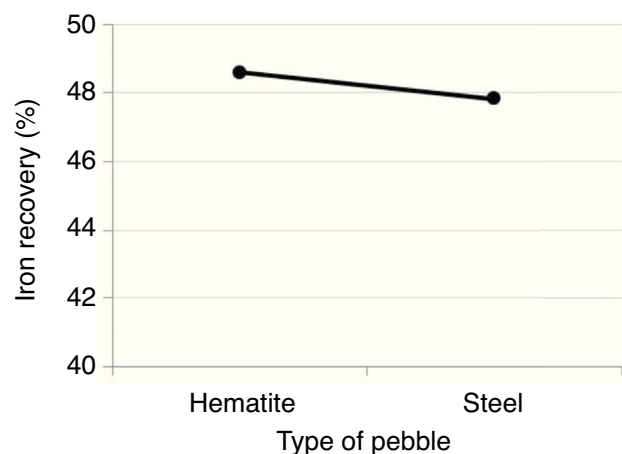
**Fig. 3 – Iron recovery versus bed mass.**

Table 5 – Results obtained using the factorial method (silica distribution).

Experiment	R1	R2	R1 + R2	Y – 1	Y – 2	Y – 3	AD	Effect	R1 – R2	(R1 – R2) ²	Tcal	^a Sig.
1	83.01	87.96	171.0	363.9	726.1	1466.5	183.31	T	–4.9	24.49	–	–
2	94.94	97.95	192.9	362.2	740.4	81.9	10.24	A	–3.0	9.05	10.73	Yes
3	83.94	85.90	169.8	368.1	44.4	2.5	0.31	B	–2.0	3.83	0.33	No
4	95.33	97.04	192.4	372.3	37.4	1.8	0.22	AB	–1.7	2.91	0.23	No
5	89.05	85.95	175.0	21.9	–1.6	14.4	1.79	C	3.1	9.62	1.88	Yes
6	96.41	96.73	193.1	22.5	4.1	–7.0	–0.87	AC	–0.3	0.10	0.92	No
7	89.64	86.84	176.5	18.1	0.6	5.8	0.72	BC	2.8	7.82	0.76	No
8	98.24	97.55	195.8	19.3	1.2	0.5	0.07	ABC	0.7	0.47	0.07	No

Sig., significance.

^a Significance occurs when Tcal > 1.86.

Through the technique of Yates Inverse Algorithm, it was possible to identify and better understand the interaction of two variables. It can be concluded that the feed granulometry was the variable that most contributed to iron recovery, while the combination of feed granulometry and bed mass provided the greatest iron recovery.

3.4. Analysis of silica in the tailings

As in the analysis of the iron recovery in concentrate, it can be noted through the last column of Table 5 that the variable A and C at their maximum levels were significant for silica distribution because the interaction showed a Tcal > Tstd = 1.86.

About the variations of results concerning the concentration of silica in the tailings, in each of the variables separately. Note that:

- i) an increase in the particle size range has generated a significant gain in the response variable, which can be observed by the slope of the corresponding line, when the range of $-2.36 + 1$ mm is replaced with $-3.35 + 1$ mm;
- ii) the exchange of the hematite pebbles by steel was the variable that contributed positively to the concentration of silica in the tailings;
- iii) the variation in bed mass also caused a small increase in the final responses.

From the Yates Inverse Algorithm, it can be noted that the feed granulometry was the most influential variable compared with the others. This variable is one that contributes to the

concentration of silica in the tailings. On the other hand, note that the feed granulometry provided the better response when it was combined with the bed mass.

3.5. Analysis of selectivity index

The last column of Table 6 shows that the BC and the ABC variables at their maximum levels are the combinations that are more significant.

It is possible to identify that the type of pebbles that make up the bed was the variable that most contributes to the selectivity index and it should be noted also that the type of pebble showed a better response combined with the change in the particle size of feed.

The highest selectivity was achieved by the interaction of pebbles with steel and 250 g of mass bed reaching a value of 4.30. But following the best combination of iron recovery (variable C) concluded that the index remained at 3.78.

3.6. Influence of operating variables on the process performance

The variation in feed particle size was the item that obtained the greatest negative effect on iron recovery when the range $-2.36 + 1$ mm was replaced by $-3.35 + 1$ mm (T → A), obtaining 51.23% less in iron recovery. When only working with hematite, the average reduction was 51.23% of iron recovery, while when working with pebbles of steel (T → B), the loss was 8.63% of recovery.

Table 6 – Results obtained using the factorial method (selectivity index).

Experiment	R1	R2	R1 + R2	Y – 1	Y – 2	Y – 3	AD	Effect	R1 – R2	(R1 – R2) ²	Tcal	^a Sig.
1	3.65	3.66	7.3	13.7	28.9	57.4	7.17	T	0.0	0.0001	–	–
2	3.2	3.18	6.4	15.1	28.5	1.1	0.13	A	0.0	0.0019	0.874	No
3	3.25	3.81	7.1	14.9	0.1	0.1	0.01	B	–0.6	0.3142	0.096	No
4	3.79	4.30	8.1	13.6	0.9	1.3	0.16	AB	–0.5	0.2517	1.092	No
5	3.28	3.78	7.1	–0.9	1.4	–0.3	–0.04	C	–0.5	0.2718	0.265	No
6	3.92	3.92	7.8	1.0	–1.3	0.8	0.10	AC	0.0	0.0000	0.646	No
7	3.66	3.07	6.7	0.8	1.9	–2.7	–0.34	BC	0.6	0.3413	2.280	Yes
8	3.18	3.70	6.9	0.1	–0.6	–2.6	–0.32	ABC	–0.5	0.2659	2.133	Yes

Sig., significance.

^a Significance occurs when Tcal > 1.86.

Replacing the background layer, and alternating hematite pebbles with steel pebbles (A → AC), the latter of which was the variable with the smallest effect on iron recovery, allowing a gain of 2.13%.

When the mass of steel pebbles was changed from 250 to 300 g, i.e. (B → BC), with the variation of the mass that makes up the bed, we obtained a decrease of 10.01% of Fe.

The largest iron recovery was 73.14% in Test 1 with the following conditions: particle size between 2.36 mm and 1 mm, the background layer formed by pebbles of hematite and operating with a mass of 250 g.

The distribution of silica, an element whose presence in the concentrate wasn't interesting because it was considered a contaminant. In fact, the aim was to obtain the highest possible distribution of silica in the tailings.

An increase in the feed particle size presented a favorable effect obtaining a 10% rise in the silica content present in the tailings. When only hematite was used, the average increase was only 10.01%, while when working exclusively with steel pebbles, the increase in silica content was 10.46%.

The replacement of the bed type, from hematite pebbles to steel pebbles, although small, presented a positive effect of 0.31% on silica distribution.

A change in the mass which filled the bed was an item that also contributed positively to the silica distribution, producing an increase of 1.79%.

It is important to note that the largest silica distribution was 98.24%, obtained in Test 8 (particle size of between 3.35 mm and 1 mm), where the bed was composed of steel pebbles and a mass of 300 g of pebbles.

The elevation of particle size increased the selectivity index, obtaining a gain of 0.13% on average. When working with only hematite, there occurred a loss of 0.031%, while by working exclusively with steel pebbles a positive result of 0.30% on average was obtained.

The alternation of the bed type, from hematite pebbles to steel pebbles, showed little positive effect on the selectivity index, an increase of 0.01% on average. It is important to stress that the alternation of bed type produces a positive effect of 0.18% when worked with a coarse particle size, and generates a negative effect of 0.15% compared with the fine particle size.

With the increase in bed mass, there was a loss of 0.04% in the selectivity index.

The highest selectivity index was 4.30 obtained in Test 4 under the following conditions: particle size between 3.35 and 1 mm, the bed composed by 250 g of steel pebbles.

4. Conclusions

It is concluded about the three variables studied, that the feed granulometry, the background layer and the bed mass interact with each other by interfering in the iron recovery, the distribution of silica and the selectivity index. By the results obtained under experimental conditions studied, it can be assured that.

The feed particle size is the factor that most contributes to the results of the iron recovery and silica distribution, although [5] claims that the feed particle size is a variable that slightly influences separation mechanisms when compared to other concentration processes.

The best iron recovery with significance was 60.71% when operating with a grain size between $-2.36 + 1$ mm, a bed made up of steel pebbles and a mass of 300 g (combination C), in the same conditions was possible to get 89.05% of silica distribution. So this was the best combination of variables.

Analyzing the selectivity index, under the conditions studied, the highest value was 4.30, obtained under the following conditions: particle size between -3.35 and $+1$ mm for the feeding with the bed composed of 250 g of steel pebbles. But, according with the best combination, C, the selective index was equal to 3.78.

Conflicts of interest

The authors declare no conflicts of interest.

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