P. BESTA, A. SAMOLEJOVÁ, R. LENORT, F. ZAPLETAL

ISSN 0543-5846
METABK 53(1) 93-96 (2014)
UDC – UDK 669.1:669.2:658.5=111

INNOVATIVE APPLICATION OF MATHEMATICAL METHODS IN EVALUATION OF ORE RAW MATERIALS FOR PRODUCTION OF IRON

Received – Prispjelo: 2012-03-08
Accepted – Prihvaćeno: 2013-05-27
Preliminary Note – Prethodno priopćenje

Current principles of evaluation of ore raw materials are usually based on a comparison of selected isolated criteria. Today's sophisticated technological level of blast furnace process requires the introduction of raw material indicators that provide global characteristics of their quality. This can´t be realized with isolated parameters only. The evaluation should incorporate the key characteristics of iron ore and convert them into a uniform evaluation parameter. This article analyzes the use of mathematical methods in the evaluation of the quality of ore raw materials.

Key words: iron ore, cost, quality, metallurgy

INTRODUCTION

The quality of ore raw materials significantly affects the technological aspects of blast furnace process [1]. The evaluation of ore raw materials and their comparison is very complicated due to the number of monitored parameters which affect the blast furnace process. The current methodology used for evaluation of the quality of ore raw materials can be generally divided into two groups of methods [2]. The first one is trying to simulate the conditions ore is exposed to when going down the stacks. The other approach is based on single-purpose tests designed to determine a selected indicator of metallurgical quality. Both of these approaches allow obtaining a number of key information about the quality of ore raw materials and about the blast furnace process. However, these methods don´t make it possible to obtain complex information which will provide a global view of the total value of the ore raw material. The evaluation of ore raw materials requires finding a system based on a multiple dimensional basis, taking into account not only the metallurgical, but also the economic and physical - chemical parameters.

The objective of this article is to analyze the use of mathematical methods based on the principle of multidimensional comparison as a tool of evaluation of ore raw materials. The evaluation will be based on data of ore raw materials from Sweden, Russia and Ukraine, which are used for production of iron in the Czech Republic.

P. Besta, A. Samolejová, R. Lenort, Faculty of Metallurgy and Materials Engineering, VŠB – Technical University of Ostrava, Czech Republic, F. Zapletal Faculty of Economics, VŠB – Technical University of Ostrava, Czech Republic

EVALUATION OF QUALITY OF IRON ORES

Iron ore is one of the most widespread minerals. The resources of this raw material can be found in virtually all parts of the world [3]. However, only selected deposits contain raw material that is suitable for use in the blast furnace. The primary aspect is always the iron content. The high-grade magnetite and hematite ores have metal content ranging from 57 to 70 %. In case of limonite ores, the Fe content can drop to 38 % [4].

The evaluation of the quality of ore raw materials is very complex and often inconsistent within the frame of different countries. Apart from the iron content and the alkalinity coefficient, a number of other relevant criteria can be included in the evaluation [5]. Generally, these criteria can be divided into several categories:

- Chemical properties - including especially iron content, alkalinity, but also the content of pollutants (S, P, Cd, Zn, Pb, As, Na_2O, K_2O).
- Physical properties - humidity, lumpiness, granulometric homogeneity, density, loose properties, porosity, magnetic properties.
- Technological properties:
- Strength characteristics - strength of ore raw materials is determined by a tumbling test and is given as a percentage share of pieces of ore raw material with after-test size larger than 6,3 mm. The determined parameters also include abrasion, which is a percentage share of pieces of ore raw materials with after-test size lower than 0,5 mm (strength in compression to a pellet is tested in case of pellets).
- Reducibility – is a sum of raw material properties, which determine the rate of conversion of iron oxide to metal by means of reducing agents. A scale of reducibility is the weight loss of ore sample per unit of time, due to the transition of oxygen into gas.

Table 1 **Parameters of the evaluated ore raw materials**

Fe ore State / location	Criterion						
	K_1	K_2	K_3	K_4	K_5	K_6	K_7
	Ore price	Content of Fe	Ore strength	Homogeneity	Content of P	Reducibility	Humidity
	$ / t	%	%	%	%	%	%
Ukraine / Poltava	151	62	75	95	0,05	48	5,2
Ukraine / Sevgok	143	63	76	92	0,04	55	6,8
Russia / Kovdor	142	64	74	90	0,04	65	1,4
Sweden / Kiruna	141	67	83	48	0,02	64	2,3

- Thermoplastic (properties) - are determined by the initial softening temperature and the end softening temperature. The difference between these two temperatures is referred to as the softening interval.

The presented list of properties of ore raw materials clearly shows that it will always be necessary to choose only certain relevant characteristics for the evaluation. The complexity of the evaluation is also given by the fact that a number of harmful elements can have different effect on the production process of iron (later steel) in different stages of production [6].

EXPERIMENTAL PART

Four used ore raw materials were compared within the scope of the realized research project in the selected metallurgical company. These were raw materials from Ukraine, Russia and Sweden, the specific location names are presented in Table 1.

The evaluation was carried out on the basis of seven relevant criteria, which are most frequently used when comparing ore raw materials in the enterprise. The evaluation requires the selection of such criteria that are important in terms of the given process, but at the same time will be available about the offered ore raw materials. Based on these facts and the long-term, experience, the following criteria have been chosen:

- K_1 Ore price ($ / ton)
- K_2 Content of Fe (%)
- K_3 Strength of ores after tumbling test, according to ISO (%)
- K_4 Homogeneity of lumpiness (Vx, %)
- K_5 Content of P (%)
- K_6 Reducibility (%)
- K_7 Humidity (%)

These parameters are also included in the international classification scales, according to which the ore materials are classified in the evaluation scales. The values for all evaluated ore raw materials have been determined for these parameters on the basis of internal company data (Table 1).

If the mathematical methods are to be used for comparing ore raw materials, it is first necessary to determine the importance (weight) of the individual criteria. This can be done by means of a qualified estimate or by means of methods that reduce the subjective nature of the decision making. When a qualified estimate is used, a weight is allocated to the individual criteria on the basis of experience and knowledge, which may not always be accurate, and it will depend on the experience of the evaluator. That is why a mathematical method which allows the process to be realized in a more exact form has been applied to set the weight system. This is the Saaty Method which is based on determination of the mutual preference of the individual criteria. All criteria are compared using an evaluation scale (Table 2) and the values of the individual bonds are arranged in the Saaty Matrix.

The elements of Saaty Matrix s_{ij} represent the estimates of shares of criteria weights (1) (how many times one criterion is more important than the other one).

$$s_{ji} = \frac{v_i}{v_j}, i, j = 1, 2, .., n \qquad (1)$$

Matrix S is of square order n x n and its elements:

$$s_{ji} = \frac{1}{v_j}, i, j = 1, 2, ..., n \qquad (2)$$

The power of preference of the individual criteria expressed according to the presented scale is written in the matrix. All the monitored criteria have been compared with each other in this way. The comparison of criteria K_1 – Ore price and K_3 – Strength of ore can be used as an example. Criterion K_1 – Ore price may be considered much more important (Table 2 evaluation 5) than criterion K_3 – Strength of ore. That is why this value is included in Saaty Matrix S in position a_{13}. Below the main diagonal, in position $a_{31,}$ the reciprocal value (1/5) representing the importance of K_3 ahead of K_1 is presented. The same procedure was used to perform the comparison of all the other criteria, where all criteria have been evaluated with each other using the binomial comparison system.

Table 2 **The criteria preference evaluation system used for the evaluation of ore raw materials**

Expression of preferences	
Numerical	Verbal
1	Criteria are equally important
3	The first criterion is slightly more important than the other one
5	The first criterion is significantly more important than the other one
7	The first criterion is significantly much more important than the other one
9	The first criterion is absolutely more important than the other one

The outcome is a completed Saaty Matrix (3) which is inherently reciprocal and its diagonal values are always one. This is due to the fact that each criterion in itself is equal.

$$S=\begin{pmatrix} 1 & 1 & 5 & 3 & 3 & 3 & 9 \\ 1 & 1 & 5 & 3 & 5 & 3 & 9 \\ 1/5 & 1/5 & 1 & 3 & 1 & 3 & 5 \\ 1/3 & 1/3 & 1/3 & 1 & 1/5 & 3 & 3 \\ 1/3 & 1/5 & 1 & 5 & 1 & 3 & 3 \\ 1/3 & 1/3 & 1/3 & 1/3 & 1/3 & 1 & 3 \\ 1/9 & 1/9 & 1/5 & 1/3 & 1/3 & 1/3 & 1 \end{pmatrix} \quad (3)$$

Standardized geometric mean of the lines (4) of Saaty Matrix is used to determine the final weights of each criterion. The calculation used to determine the weight of criterion K_1 is demonstrated in equation (4).

$$w_i=\frac{\left[\prod_{j=1}^{n} s_{ij}\right]^{\frac{1}{n}}}{\sum_{k=1}^{n}\left[\prod_{j=1}^{n} s_{kj}\right]^{\frac{1}{n}}}=\frac{2,7584}{9,4599}=0,2916 \quad (4)$$

The same way was used to determine the weights of all the other criteria (Table 3). The weight value determines the importance of each criterion.

The most important criterion determined using Saaty Method was criterion no. 2 - the content of iron (weight of 0,3137), followed by no. 1 - price (weight of 0,2916), and the third most important criterion for the evaluation of iron ore is no.5 - content of P (weight of 0,1237). The least important criterion was no. 7 - humidity of ore (weight of 0,0280).

The identified importance of the individual criteria for the evaluation of ore raw materials was used in their comparison. The comparison of the monitored ore raw materials can take advantage of the method of distance from a dummy option, which is based on the Euclidean distance measurement in a multidimensional space. The principle of the distance method from a dummy option is to find the distance of the individual options from the so-called fixed option, which can be an ideal option having the best parameters for all the criteria. The calculation of the distance of each option from a dummy one (D_j) can be performed on the basis of equation (5).

$$D_j=\sqrt{\sum_{i=1}^{n} v_i \times \left(\frac{x_i^{*}-x_{ij}}{x_i^{*}-x_i^{0}}\right)^2} \quad (5)$$

The total value of the distance from a dummy option is essentially a sum of partial deviations from the ideal value of each criterion. The option of ore which has the smallest total value is rated as optimal. The distance from a dummy option was determined for all ore options and the overall sequence was determined afterwards. The results of all the monitored ore options are shown in Table 4. The identified distance from a dummy option represents the total value of the ore. The last line of Table 4 shows the sequence of the monitored ore raw materials.

RESULTS

The evaluated ore raw materials are used in a number of metallurgical enterprises in Central Europe. Transportation cost savings represent a great advantage. In terms of the quality of the ore raw materials, much more

Table 3 **Weights of criteria used for ore evaluation determined by Saaty Method**

Criterion	K_1	K_2	K_3	K_4	K_5	K_6	K_7
	Ore price	Content of Fe	Ore strength	Homogeneity	Content of P	Reducibility	Humidity
$\left[\prod_{j=1}^{n} s_{ij}\right]^{\frac{1}{n}}$	2,7584	2,9672	1,0876	0,6789	1,1698	0,5334	0,2647
$\sum_{k=1}^{n}\left[\prod_{j=1}^{n} s_{kj}\right]^{\frac{1}{n}}$	9,4599	9,4599	9,4599	9,4599	9,4599	9,4599	9,4599
Criterion weight	0,2916	0,3137	0,1150	0,0718	0,1237	0,0562	0,0280

Table 4 **Determination of the distance from a dummy option for the monitored ores**

	v_i	x_i^*	x_i^0	Ukraine Poltava	Ukraine Sevgok	Russia Kovdor	Sweden Kiruna
K_1 – Price	0,2916	141	151	0,2916	0,0116	0,0029	0
K_2 – Content of Fe	0,3137	67	62	0,3137	0,2008	0,1129	0
K_3 – Ore strength	0,1150	83	74	0,0908	0	0,1150	0,0696
K_4 – Homogeneity	0,0718	48	95	0,0718	0,0629	0	0,0573
K_5 – Content of P	0,1237	0,02	0,05	0,1237	0,0549	0,0549	0
K_6 – Reducibility	0,0562	65	48	0,0562	0,0194	0	0,0002
K_7 – Humidity	0,0280	1,4	6,8	0,0138	0,0280	0	0,0007
			Σ	0,9616	0,3776	0,2857	0,1278
			D_j	0,9806	0,6144	0,5345	0,3575
			Sequence	4.	3.	2.	1.

valuable resources from Australia or Brazil can be used as well; however they are significantly more expensive, of course. At the same time, the transportation of ore raw materials is also significantly more expensive due to the distance and the costs associated with loading and unloading of the raw materials. The compared ores have been evaluated according to seven key criteria. Their order was determined on the basis of application of the mathematical methods of multi-criteria decision making:

Sweden / Korun (The value of distance from a dummy option is 0,3575)

Russia / Kovdor (The value of distance from a dummy option is 0,5345)

Ukraine / Sevgok (The value of distance from a dummy option is 0,6144)

Ukraine / Poltava (The value of distance from a dummy option is 0,9806)

The lower the value, the better the ore material is. This is given by measuring the distance to an ideal option, with optimal values of all criteria. That is why ore raw material from Sweden from the location of Korun was by far the best. This is also due to the fact that the ore has the highest content of iron, which has been identified as the most important criterion. The second place was taken by ore from Russian location Kovdor. The worst ore raw materials, based on the evaluated data, come from Ukraine from Sevgok and Poltava. If we look at the total determined values of ores, it is evident that the best ore raw material has almost three times better evaluation in comparison with the last ore from Poltava. Ore raw materials from Ukraine are most commonly used by metallurgical companies in the Czech Republic. This is primarily due to their low price, but also the logistic availability. However, it is apparent from the evaluation that these ores are significantly worse. These raw materials are also significantly more acidic, which causes higher costs resulting from the consumption of alkaline additives. Acidic ores may also have different and varying metallurgical properties. All these factors must be taken into account in the evaluation of ore raw materials. Evaluation of iron ores using only one criterion can't be effective in the long run, especially if the criterion is the price of ore.

CONCLUSION

The use of mathematical methods in the evaluation of ore raw materials can be an interesting tool allowing exact comparison of the individual ores using a variety of criteria. The experience from the operation of iron-foundry manufacturing facilities shows that to evaluate ore raw materials by a single criterion is not sufficient. The applied methodology allows you to compare ore raw materials according to a number of criteria, which have completely inhomogeneous indicators. The performed comparison is then concentrated into a single indicator which is used for the evaluation. The obtained results can serve for comparison of the individual ore raw materials, but also as a tool for the analysis of newly offered ores. At the same time, the determined ore quality can be used for long term strategic decisions regarding the purchase of ore raw materials.

Acknowledgement

The work was supported by the specific university research of Ministry of Education, Youth and Sports of the Czech Republic No. SP2012/12 and No. SP2013/19.

REFERENCES

[1] Ch. K. Gupta, Chemical metallurgy: Principles and Practice, John Wiley & Sons, Weinheim, 2006, p. 378-379.

[2] R. Yin, Metallurgical Process Engineering, Springer, New York, 2011, pp. 120-121.

[3] S. Bakalarczyk, P. Pomykalski, E. Weiss, Innovativeness of metallurgical production enterprises, In Metal 2011: 20th Anniversary International Conference on Metallurgy and Materials. Ostrava: TANGER, 2011, pp. 1298-1302. ISBN 978-80-87294-24-6.

[4] L. K. Reddy, Principles of engineering metallurgy, New Age International, New Delhi, 2007, p. 201.

[5] A. Butts, Metallurgical Problems, Johnston Press, 2008, pp. 67-68.

[6] P. Besta, K. Janovská, L. Hula, Logistika a řízení zásob v hutní výrobě. Hutnické listy, 65 (2012) 4, pp. 51-55.

Note: The responsible translator for English language is Petr Jaroš (English Language Tutor at the College of Tourism and Foreign Trade, Goodwill - VOŠ, Frýdek-Místek, the Czech Republic)