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Possibilities of Evaluation of Complex Quality of Ore Raw Materials Using Managerial Decision-making Tools

Možnosti hodnocení komplexní kvality rudných surovin při využití manažerských rozhodovacích nástrojů

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The article examines the experimental use of mathematical tools of multi-criteria decision making in the evaluation of ore raw materials quality. For the needs of the selected metallurgical company, the quality of three types of ore raw materials from different sites was evaluated. The evaluation was based on the quantification of eight key criteria. Ore raw materials from Russia, Sweden and Brazil were analyzed. In the first step the evaluation criteria and their weights were selected. The Saaty method based on pairwise comparison was used to determine the weights. The complex quality of the monitored ore raw materials was evaluated by the distance method from the imaginary variant. The solution was implemented as part of research focused on the evaluation of the complex quality of ore raw materials.

Key words: *iron; reduction; cost; comparison; multi-criteria decision*

Výrobci surového železa mohou využívat široké spektrum rudných surovin z odlišných nalezišť. Kvalita rudných surovin zásadně ovlivňuje technologické aspekty vysokopecního procesu, ale také jeho nákladovost. Pro hodnocení rudných surovin můžeme používat široké spektrum kritérií, která mají charakter chemických, fyzikální, technologických nebo ekonomických parametrů. Výrobci železa musí často provádět vyhodnocování nabídek na dodávku rudných surovin v rámci svých nákupních procesů. Problém hodnocení spočívá v širokém spektru parametrů, které můžeme sledovat. Tyto parametry mají často zásadně odlišný charakter. Jednotliví dodavatelé také o nabízených rudných surovinách poskytují odlišný soubor kritérií. Hutní podniky pak řeší porovnávání jednotlivých rudných surovin na základě velkého souboru nesrovnatelných kritérií. Zajímavou možností je syntetizovat kategoriálně odlišná kritéria do jednoho ukazatele. Toto umožňují matematické nástroje vícekriteriálního rozhodování. V rámci realizovaného výzkumu byly posouzeny rudné suroviny z Ruska, Švédska a Brazílie pomocí matematických nástrojů umožňujících vícekriteriální hodnocení. Sledované rudné suroviny byly porovnány z hlediska jejich komplexní kvality na základě osmi klíčových kritérií. Pro hodnocení byla využitá Saatyho metoda na bázi párového porovnání a metoda vzdálenosti od fiktivní varianty. Článek se zabývá rozborem realizovaného výzkumu, zaměřeného na možnosti komplexního hodnocení kvality rudných surovin.

Klíčová slova: *železo; redukce; ruda; náklady; komparace; multikriteriální rozhodování*

Iron ore is one of the widely spread minerals. Resources can be practically found in all parts of the world. However, only selected deposits contain raw material that is suitable for use in a blast furnace. The primary aspect is always the iron content. For rich magnetite and hematite ores, the metal content ranges from 57 to 65 %. In the case of limonite ores, the iron content may fall to 38 % [1]. However, the content of the metal is only one selected indicator that evaluates the quality of the ore raw material. The complexity of ore evaluation is due to the nature of the blast furnace process. This can be seen as a set of a large number of physicochemical, thermal and mechanical processes that do not take place separately from this raw material, but in certain interrelationships [2]. In the same way, we can comprehensively look at the quality of ore raw materials.

1. Ore raw materials and evaluation options

Ore materials can be basically divided into four major categories: anhydrous oxides, hydrated oxides, carbonates and silicates. Anhydrous oxides are among the most important and include hematite (Fe_2O_3) and magnetite (Fe_3O_4). Hydrated oxides contain chemically bound water and are primarily hydro hematite ($Fe_2O_3 \cdot nH_2O$, $n < 1$), Götit ($Fe_2O_3 \cdot H_2O$, $n = 1$) or limonite ($Fe_2O_3 \cdot nH_2O$, $1 < n < 1.5$). Less important are groups of ores, such as carbonates (siderite $FeCO_3$) or silicates (chamosite $[Fe, Mg]_{15}Al_{10}Si_{11}O_{52} \cdot 16H_2O$) [3].

The quality of ore raw materials fundamentally affects the technological aspects of the blast furnace process. However, we can often observe dozens of completely different criteria when evaluating ore raw materials. In general, we can classify these criteria into the following categories [3]:

- Chemical properties

  Dominant above all is the iron content, which fundamentally affects the efficiency of the production process. Another important aspect is the basicity that is significant in terms of blast furnace slag formation. The key is also the content of harmful elements that can enter the blast furnace process (S, P, Cd, Zn, Pb, As, Na_2O, K_2O, Hg).

- Physical properties

  These properties may affect the course of the blast furnace process. Their monitoring concerns not only the ore raw materials themselves but all metal-bearing materials, coke and basic additives. (moisture, lumpiness, granulometric homogeneity, density, bulk properties, porosity, magnetic properties).

- Technological properties

  These properties are related to the behavior of the ore in the blast furnace process. These are mainly strength characteristics, reducibility and thermoplastic properties.

It is obvious from the above that several parameters can be used for the evaluation of ore raw materials, which makes the overall quality assessment considerably more difficult. The current methodologies for evaluating the quality of ore raw materials can generally be divided into two distinct groups. The first group attemps to simulate the conditions, to which the ore is exposed during descent charge in the blast furnace shaft. The second group of methods consists of tests designed to determine the selected metallurgical quality indicator. Both of these approaches make it possible to obtain a number of relevant information on the quality of ore raw materials and the course of the blast furnace process [4]. However, it will always be just monitoring and comparing the selected isolated indicators without the possibility of synthesizing multiple parameters. The decision to choose the appropriate ore raw material is one of the most strategic importance for the metallurgical company [5]. It is very important to create and use a consistent system of evaluation and selection of feedstocks. An alternative to these approaches is the possibility of using multi-criteria decision making, which allows to aggregate a wide range of information into selected indicators that can be used for decision making. Iron producers are under increasing pressure not only from customers, but also from the competition, especially in relation to the quality, but also the price of the produced metal. Therefore, optimizing all processes requires accurate monitoring and evaluation of feedstock quality.

2. Experimental part

Within the framework of the realized research three types of ore raw materials were analyzed in the conditions of the selected iron producer. Ore raw materials came from Russia, Sweden and Brazil. Eight key criteria were selected for evaluation and they were selected across the three above mentioned categories. The highest number of criteria is that of chemical character. These can be considered as key parameters in a number of aspects of the blast furnace process. At the same time, chemical criteria are the most commonly used by iron ore suppliers. Tab. 1 shows the compiled set of criteria and their specific values for the three monitored ores. In terms of metal bearing content, the richest ore raw material is from Brazil, which is also the least cost-effective. The values of other criteria can be considered very similar. The use of multicriterial decision-making tools will make it possible to synthesize all the monitored parameters. The evaluation will then be aggregated into one comprehensive indicator.

Tab. 1 Criteria values for monitored types of ore raw materials
Tab. 1 Hodnoty kritérií pro sledované druhy rudných surovin

Criteria			Raw ore		
			Russia Kursk	**Sweden Kiruna**	**Brazil Carajás**
K1	Fe content	%	57.8	59.1	68.1
K2	P content		0.034	0.028	0.031
K3	S content		0.014	0.014	0.009
K4	SiO_2 content		5.3	5.6	1.4
K5	Al_2O_3 content		0.88	0.98	1.14
K6	Homogeneity		25	33	43
K7	Reducibility		63	62	64
K8	Price	S/t	64	66	73

In order to use the tools of multi-criteria decision making, it is necessary in the first step to determine the weights (importance) of the individual criteria. One of the possibilities of determining weights is the principle of dividing 100 points among the criteria. The value assigned then represents the specific weight of the criterion. However, this procedure is considerably burdened by the subjective nature of decision-making. An alternative procedure to this is a set of methods that are based on the principle of pairwise comparison. Therefore, the Saaty method, which belongs to the group of methods, has been applied to determine the weights. The principle of the Saaty method is based on the quantification of the paired decisions made. The respondent binomially compares the meaning of two criteria on a defined scale. A scale of 1 – 9, as shown in Tab. 2, was used for the evaluation. The respondent thus evaluates the preference intensity between the two criteria. In this way, all pairs of criteria are compared.

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The intensity of the preferences of the ith criterion against the jth criterion is then subdivided into a Saaty matrix, whose s_{ij} elements represent estimates of the weights of the criteria. The assembled Saaty matrix is a square order.

Tab. 2 Evaluation of preference intensity [6]
Tab. 2 Hodnocení intensity preferencí [6]

Expression of preferences	
Numerical	**Verbal**
1	The criteria are equally important
3	The first criterion is slightly more important than the other
5	The first criterion is more important than the other
7	The first criterion is strongly more important than the other
9	The first criterion is absolutely more important than the other

Therefore, the respondent made a comparison of all defined criteria. As an example, an evaluation of the significance of the criteria of the content of Fe and the content of P can be given. This evaluation was written in the assembled Saaty matrix at position s_{12} (7) and s_{21} (1/7). This is due to the reciprocal principle of writing an evaluation into a compiled matrix. All other criteria were compared in the same way. Based on these partial evaluations the assembled Saalty matrix (1) is shown below:

$$S = \begin{pmatrix} 1 & 7 & 7 & 5 & 5 & 9 & 3 & 3 \\ 1/7 & 1 & 1/3 & 3 & 3 & 3 & 5 & 1/5 \\ 1/7 & 3 & 1 & 5 & 5 & 7 & 1/3 & 1/7 \\ 1/5 & 1/3 & 1/5 & 1 & 1 & 3 & 1/5 & 1/3 \\ 1/5 & 1/3 & 1/5 & 1 & 1 & 3 & 1/5 & 1/3 \\ 1/9 & 1/3 & 1/7 & 1/3 & 1/3 & 1 & 1/5 & 1/7 \\ 1/3 & 1/5 & 3 & 5 & 5 & 5 & 1 & 3 \\ 1/3 & 5 & 7 & 3 & 3 & 7 & 1/3 & 1 \end{pmatrix} \quad (1)$$

The evaluation of the comparisons made is based on the calculation of the weighted geometric average of the individual rows of the matrix in eq. (1). The calculation was executed in MS Excel.

$$w_i = \frac{\left[\prod_{j=1}^{n} s_{ij}\right]^{\frac{1}{n}}}{\sum_{k=1}^{n}\left[\prod_{j=1}^{n} s_{kj}\right]^{\frac{1}{n}}} \quad (2)$$

where w_j is the weight of criterion, s_{ij} and s_{kj} are elements of the Saaty matrix.

The calculations made for the individual steps (rows) and the total weights of the criteria are shown in Tab. 3. Based on executed comparisons and their quantification, clearly the most important was the criterion K1 – content with weight 0.372. The least significant criterion is K6 – homogeneity of lumpiness (0.022).

Tab. 3 Determination of criteria weights
Tab. 3 Stanovení vah kritérií

	K1	K2	K3	K4	K5	K6	K7	K8
$\left[\prod_{j=1}^{n} s_{ij}\right]^{\frac{1}{n}}$	4.213	1.031	1.171	0.477	0.477	0.253	1.715	1.989
$\sum_{k=1}^{n}\left[\prod_{j=1}^{n} s_{ij}\right]^{\frac{1}{n}}$	11.324	11.324	11.324	11.324	11.324	11.324	11.324	11.324
Weight of criterion	0.372	0.091	0.103	0.042	0.042	0.022	0.151	0.176

Detected weights will be further used in the multi-criteria evaluation of these ore raw materials. Method of distance from the fictitious variant was used for comparing them. The method of distance from the fictitious variant is based on quantification of deviations of individual criteria from the ideal variant. The resulting value determined by eq. (3) then represents the sum of the deviations of all criteria from the ideal variant, with the simultaneous quantification of weights.

$$D_j = \sqrt{\sum_{i=1}^{n} v_i \times \left(\frac{x_i^* - x_{ij}}{x_i^* - x_i^0}\right)^2} \quad (3)$$

Where D_j is the distance from the fictional variant, v_j – weighs the criterion, x_{ij} – the value of each of the criteria for individual ores, x_i^* – the best value with respect to the ith criterion, x_i^0 – the worst value relative to the ith criterion.

Tab. 4 Determined evaluation of monitored raw ore
Tab. 4 Zjištěné hodnocení sledovaných rudných surovin

	v_i	x_i^*	x_i^0	Russia Kursk	Sweden Kiruna	Brazil Carajás
K1	0.372	68.1	57.8	0.372	0.284	0
K2	0.091	0.028	0.034	0.091	0	0.023
K3	0.103	0.009	0.014	0.103	0.103	0
K4	0.042	1.4	5.6	0.036	0.042	0
K5	0.042	0.88	1.14	0	0.006	0.042
K6	0.022	25	43	0	0.004	0.022
K7	0.151	64	62	0.038	0.151	0
K8	0.176	64	73	0	0.009	0.176
			∑	0.640	0.599	0.263
			D_j	0.800	0.774	0.513
			Order	3.	2.	1.

Tab. 4 shows the evaluation performed methodologically. Column vi indicates the weights of the relevant criterion that were used. The weights were determined using the Saaty method in the previous step. For each monitored ore raw material, the calculated value of the partial distance from the fictitious variant for each criterion is then calculated according to (3). The final rating is given in the D_j line for all three ore raw material. In the last row of the tab. 4 is the final ranking according to the found values. The method quantifies the distance from the ideal variant, so the lower value (D_j) represents a better ore raw material.

3. Results and discussion

To evaluate ore raw materials a multi-criteria decision-making was used. In the first step, weights for all criteria were determined by the Saaty method. The found weights were further used within the applied distance method from the fictitious variant. This method was used to compare ore raw materials from Russia, Sweden and Brazil. The evaluation results are shown in Tab. 4. The ore raw materials can be sorted in descending order based on a specified distance value from the dummy variant (D_j).

1. Brazil – 0.513
2. Sweden – 0.774
3. Russia – 0.800

The best-rated ore is from Brazil. This is mainly due to the iron content, which is significantly highest. Iron content was also identified as the most important criterion, with the highest weight (0.372), which also affected the final result. At the same time, however, the ore raw material from Brazil is the least profitable. Out of the eight criteria, this ore had the best value in four parameters. If we evaluate the synthesis of all the mentioned parameters it is the most valuable ore from the analyzed ones. Ore raw materials from Sweden and Russia are significantly worse, according to the observed values. However, the calculated distance from the ideal variant is very similar for both ores. Based on this, the two ores can be considered to be qualitatively comparable. In the case of ore from the Russian deposits, it can also be stated that it was identified as the worst, even though its price is the lowest. Therefore, if we had only selectively evaluated the ores by their price, the final ranking would be diametrically different.

Conclusions

The use of multi-criteria evaluation for comparison of the quality of ore raw materials offers an interesting alternative for customers. A great advantage of the applied procedure is the possibility of synthesis of a large number of parameters into one indicator. In the case of the distance-to-fictitious method applied, it is still possible to easily convert the calculated values into a percentage form, which further simplifies the interpretation of the results. In addition, the method allows us to quantify the specific value of the criteria. Therefore, it is not only the order of the criteria values but the processing of specific differences. Moreover, the use of methods is very algorithmic, which supports the possibility of using even common office applications. It is possible to use the aforementioned procedure for the operative comparison of the offered raw materials for the raw material buyers. Logically, in the final purchase decision it will also be necessary to consider some other aspects. Nevertheless, it is possible to use this procedure as one of the supporting documents for the support of metallurgical companies' purchasing processes.

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