INNOVATION IN THE SYSTEM OF IRON ORE EVALUATION

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Abstract
The main objectives of blast furnace operators include the maximum production of pig iron of the required chemical composition at minimal cost. This can be ensured only with quality raw material base and a trouble-free operation of the blast furnace. The evaluation of ore raw materials and their comparison is quite complicated due to the number of monitored parameters affecting the blast furnace process. Current methods used for evaluating the quality of the ore blast furnace raw materials can be generally divided into two distinct groups. The first one tries to simulate the conditions which the ore going down the blast furnace stack is exposed to. The other approach is based on single-purpose tests performed in order to determine the selected indicator of metallurgical quality. Both of these approaches allow obtaining a number of key information related to the quality of ore raw materials and the blast furnace process. Unfortunately, these methods cannot help you to obtain complex information that will provide a global view of the "quality class" of the given ore raw material. For the evaluation of ore raw materials, it is necessary to find a system based on a multi-dimensional basis, taking into account not only the metallurgical, but also the economic and physical and chemical parameters. The complexity of the evaluation of ore raw material is mainly based on the completely different character of the monitored parameters. The mathematical methods of multi-criteria decision-making appear to be very suitable to use for the evaluation of ore raw materials. The aim of this article is to analyze the possible utilization of these tools in the evaluation of ore raw materials as operational tools for their comparison.

Keywords: iron ore, pollutants, blast furnace

1. INTRODUCTION
The blast furnace process is a set of large number of physical and chemical, thermal and mechanical processes, which do not take place separately, but rather in some kind of interrelation [1]. These partial phenomena also include, alongside the reduction of iron oxides and the residual elements of pig iron as the primary task of the blast furnace, the processes of fuel combustion in a well, the counterflow of gas, charge and the liquid products of smelting, the dissociation processes, and the reactions in solid and liquid phases.

The quality of ore materials significantly affects the technological aspects of the blast furnace process [2]. However, when evaluating ore raw materials, we can often monitor dozens of completely different criteria. In terms of categories, the important parameters can be classified into three groups: chemical, physical, and technological. The elementary chemical parameters of ore raw materials include the iron content, the amount of harmful substances (sulphur, phosphorus, zinc, alkali), but also for example the alkalinity [3]. The important physical properties may include especially humidity, lumpiness, porosity, and magnetic properties. The technological properties include the characteristics of strength, reducibility and thermoplastic properties. This list clearly indicates that the evaluation of ore raw materials can use dozens of parameters, which, however, significantly limits the possibility of comparison.

The current methodologies for assessing the quality of ore blast furnace raw materials can be generally divided into two different groups [4]. The first one is trying to simulate the conditions ore is exposed to when going down the blast furnace stack. The second method relies on benchmark tests designed to determine...
the selected indicator of metallurgical quality [5]. Both of these approaches allow obtaining a number of relevant information about the quality of the ore raw materials and about the flow of the blast furnace process. The limitation of these methods lies in the fact that they will always be based on the evaluation of isolated criteria, which do not allow quantifying the quality of one ore raw material by means of one comparable indicator that would take into account several factors.

A research focused on the use of mathematical methods of multi-criteria decision-making for comparison of ore raw materials was conducted within the monitored metallurgical plant. The article deals with the analysis of the possible utilization of these methods and it shows the results of a long-term research focused on the comparison of ore raw materials.

2. PROBLEM FORMULATION

The evaluation of the quality of ore charge can be realized from different perspectives. In essence, we can identify three basic options [6]:

- evaluation of the behaviour of ore when going down the stack
- single-purpose benchmark tests intended to determine a selected metallurgical indicator
- complex approaches to the evaluation of ores.

The issue of the assessment of ore raw materials is complicated due to the wide range of relevant criteria that evaluate completely different characteristics and that have different size indicators [7]. This vastly complicates the comparison of the individual types of ores. That is why a model of the evaluation of ore raw materials had been prepared in the monitored blast furnace plant, where eleven kinds of ore raw materials in total were evaluated from the point of view of seven relevant criteria.

If the evaluation of ore raw materials is to be used for operational decision-making, it is necessary to work with the available information. Seven key areas, which will be taken into account during the evaluation, have been defined on the basis of these facts. The criteria have been defined through brainstorming, attended both by the personnel of purchasing department and by the experts from iron production technology department. In this way, the following criteria have been selected for the evaluation of ore raw materials:

1. Price of ore ($/ton)
2. Content of iron (%)
3. Strength of ore after tumble test, according to ISO (%)
4. Homogeneity of lumpiness ($V_x$, %)
5. Amount of P (%) 
6. Reducibility (%)
7. Humidity (%)

The values of the evaluated criteria were determined for all the monitored ores. The data were obtained from long-term records of used ore raw materials. The details of all raw materials are shown in Table 1. The evaluation of ore raw materials took advantage of the methods of multi-criteria decision-making.
Table 1 Values of criteria of monitored ore raw materials

<table>
<thead>
<tr>
<th>Option of evaluated ores</th>
<th>K1</th>
<th>K2</th>
<th>K3</th>
<th>K4</th>
<th>K5</th>
<th>K6</th>
<th>K7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price of ore</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Content of iron</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strength of ore</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Homogeneity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amount of phosphorus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reducibility</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Humidity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit</td>
<td>$/t</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>V1</td>
<td>151</td>
<td>62</td>
<td>75</td>
<td>95</td>
<td>0,05</td>
<td>48</td>
<td>5,2</td>
</tr>
<tr>
<td>V2</td>
<td>143</td>
<td>63</td>
<td>76</td>
<td>92</td>
<td>0,04</td>
<td>55</td>
<td>6,8</td>
</tr>
<tr>
<td>V3</td>
<td>142</td>
<td>64</td>
<td>74</td>
<td>90</td>
<td>0,04</td>
<td>65</td>
<td>1,4</td>
</tr>
<tr>
<td>V4</td>
<td>141</td>
<td>67</td>
<td>83</td>
<td>48</td>
<td>0,02</td>
<td>64</td>
<td>2,3</td>
</tr>
<tr>
<td>V5</td>
<td>140</td>
<td>61</td>
<td>79</td>
<td>79</td>
<td>0,03</td>
<td>66</td>
<td>6,2</td>
</tr>
<tr>
<td>V6</td>
<td>139</td>
<td>65</td>
<td>74</td>
<td>90</td>
<td>0,05</td>
<td>64</td>
<td>4,7</td>
</tr>
<tr>
<td>V7</td>
<td>142</td>
<td>66</td>
<td>82</td>
<td>52</td>
<td>0,01</td>
<td>69</td>
<td>2,9</td>
</tr>
<tr>
<td>V8</td>
<td>138</td>
<td>63</td>
<td>75</td>
<td>122</td>
<td>0,04</td>
<td>61</td>
<td>3,3</td>
</tr>
<tr>
<td>V9</td>
<td>149</td>
<td>64</td>
<td>77</td>
<td>89</td>
<td>0,04</td>
<td>63</td>
<td>3,9</td>
</tr>
<tr>
<td>V10</td>
<td>148</td>
<td>61</td>
<td>80</td>
<td>96</td>
<td>0,04</td>
<td>64</td>
<td>5,1</td>
</tr>
<tr>
<td>V11</td>
<td>152</td>
<td>62</td>
<td>75</td>
<td>91</td>
<td>0,05</td>
<td>62</td>
<td>4,2</td>
</tr>
</tbody>
</table>

The monitored ore raw materials were schematically marked by symbols of V1 – V11, all the materials are anhydrous oxides based on hematite and red iron.

3. EXPERIMENTAL WORK

The data of ore raw materials as listed in Table 1 must be adjusted before further use. For further calculations and evaluations of the various options of ores, a correction of two criteria was made for the purpose of simplification. The clearer type of the matrix form required all values of the content of phosphorus (K5) to be multiplied by a constant of 100. The data of humidity (K7) were adjusted the same way. They were multiplied by a constant of 10. Before the criteria matrix was assembled, it was necessary to unify the individual types of criteria. The evaluation includes both the criteria of maximization (K2, K3, K6), and the criteria of minimization (K1, K4, K5, K7). As a result of that, all the minimization criteria were transferred into maximization ones. This was realized by subtracting the other values in the individual criteria from the worst values in the minimization criterion. Once this transformation had been performed, a modified criteria matrix (1) was put together, where all the criteria were already of maximization type.

The method of weighted sum, based on the concept of maximization of yield and counting only with linear function of yield, was used to compare the ore raw materials. This method belongs to the category that includes procedures requiring cardinal information about the criteria. The procedure is based on the creation of a standardized criterion matrix R = (r_{ij}), the elements of which are obtained from the modified criteria matrix Y1 = (y_{ij}) through a transformation according to formula (2).
When an additive form of the multi-criteria function of yield is used, then the yield of option \( a_i \) equals:

\[
u_i = \sum_{j=3}^{k} v_j r_{ij}\]

(3)

The option that achieves maximum yield value is marked as the best, or you can arrange the options according to decreasing values of yield. The ideal and basic values of vectors were determined in the first step. These values are based on the criterion matrix and have the following form:

\[
H = (14, 67, 83, 74, 4, 69, 54) - \text{ideal} \quad (4)
\]

\[
D = (0, 61, 74, 0, 0, 48, 0) - \text{basic} \quad (5)
\]

The transformation formula (2) helped us to determine the element values of normalized criteria matrix whose values represent the level of yield of the given option according to certain criterion. An example of the calculation for an element located in the first line and in the first column of the criteria matrix can be written as follows:

\[
r_{ij} = \frac{y_{ij} - D_j}{H_j - D_j} = \frac{14 - 0}{14 - 0} = 0.07
\]

(6)

The values of the individual criteria within the standardized criteria matrix were then multiplied by the respective weight of the given criteria. The weights used for the monitered criteria represented the values that are used for the evaluation of ore raw materials in the observed metallurgical company. The values of the weights are shown as a vector in (4).

\[
v = (0.2046; 0.2219; 0.1207; 0.0949; 0.1027; 0.0920; 0.1275) \quad (7)
\]

The total yield is the sum of all partial contributions of each observed criterion of the monitored ore option. The values of all the criteria took into account the value of the weight of each criterion. The order of the individual criteria was determined on the basis of the defined yield, and the results are shown in Table 2. The option with the highest yield value was classified in the first place.
Matrix R is the assembled standardized criteria matrix.

\[
\begin{pmatrix}
0.07 & 0.16 & 0.11 & 0.36 & 0.25 & 0 & 0.29 \\
0.64 & 0.33 & 0.22 & 0.40 & 0.25 & 0.33 & 0 \\
0.71 & 0.50 & 0 & 0.43 & 0.25 & 0.80 & 1 \\
0.78 & 1 & 1 & 1 & 0.75 & 0.76 & 0.83 \\
0.85 & 0 & 0.55 & 0.58 & 0.50 & 0.85 & 0.11 \\
0.92 & 0.66 & 0 & 0.43 & 0.50 & 0.76 & 0.38 \\
0.71 & 0.83 & 0.88 & 0.94 & 0.25 & 1 & 0.72 \\
1 & 0.33 & 0.11 & 0 & 0.25 & 0.61 & 0.64 \\
0.21 & 0.50 & 0.33 & 0.44 & 0.25 & 0.71 & 0.53 \\
0.28 & 0 & 0.66 & 0.35 & 0.25 & 0.76 & 0.31 \\
0 & 0.16 & 0.11 & 0.41 & 0 & 0.66 & 0.48
\end{pmatrix}
\]

The monitored ore options were evaluated in the following order: V4, V7, V6, V3, V8, V5, V9, V2, V10, V11, and V1. The determined yield can also be understood as the total value of the ore raw material quality, which was established on the basis of the defined criteria.

**Table 2** Evaluation of order of monitored types of ore raw materials

<table>
<thead>
<tr>
<th></th>
<th>K₁</th>
<th>K₂</th>
<th>K₃</th>
<th>K₄</th>
<th>K₅</th>
<th>K₆</th>
<th>K₇</th>
<th>Yield</th>
<th>Order</th>
</tr>
</thead>
<tbody>
<tr>
<td>V₁</td>
<td>0.0143</td>
<td>0.0355</td>
<td>0.0132</td>
<td>0.0341</td>
<td>0.0256</td>
<td>0</td>
<td>0.0369</td>
<td>0.1599</td>
<td>11.</td>
</tr>
<tr>
<td>V₂</td>
<td>0.1309</td>
<td>0.0732</td>
<td>0.0265</td>
<td>0.0379</td>
<td>0.0256</td>
<td>0.0303</td>
<td>0</td>
<td>0.3247</td>
<td>8.</td>
</tr>
<tr>
<td>V₃</td>
<td>0.1452</td>
<td>0.1109</td>
<td>0</td>
<td>0.0408</td>
<td>0.0256</td>
<td>0.0736</td>
<td>0.1275</td>
<td>0.5238</td>
<td>4.</td>
</tr>
<tr>
<td>V₄</td>
<td>0.1595</td>
<td>0.2219</td>
<td>0.1207</td>
<td>0.0949</td>
<td>0.0770</td>
<td>0.0699</td>
<td>0.1058</td>
<td>0.8499</td>
<td>1.</td>
</tr>
<tr>
<td>V₅</td>
<td>0.1739</td>
<td>0</td>
<td>0.0663</td>
<td>0.0550</td>
<td>0.0513</td>
<td>0.0782</td>
<td>0.0140</td>
<td>0.4389</td>
<td>6.</td>
</tr>
<tr>
<td>V₆</td>
<td>0.1882</td>
<td>0.1464</td>
<td>0</td>
<td>0.0408</td>
<td>0.0513</td>
<td>0.0699</td>
<td>0.0484</td>
<td>0.5452</td>
<td>3.</td>
</tr>
<tr>
<td>V₇</td>
<td>0.1452</td>
<td>0.1841</td>
<td>0.1062</td>
<td>0.0892</td>
<td>0.0256</td>
<td>0.0920</td>
<td>0.0918</td>
<td>0.7343</td>
<td>2.</td>
</tr>
<tr>
<td>V₈</td>
<td>0.2046</td>
<td>0.0732</td>
<td>0.0132</td>
<td>0</td>
<td>0.0256</td>
<td>0.0561</td>
<td>0.0816</td>
<td>0.4545</td>
<td>5.</td>
</tr>
<tr>
<td>V₉</td>
<td>0.0429</td>
<td>0.1109</td>
<td>0.0398</td>
<td>0.0417</td>
<td>0.0256</td>
<td>0.0653</td>
<td>0.0675</td>
<td>0.3941</td>
<td>7.</td>
</tr>
<tr>
<td>V₁₀</td>
<td>0.0572</td>
<td>0</td>
<td>0.0796</td>
<td>0.0332</td>
<td>0.0256</td>
<td>0.0699</td>
<td>0.0395</td>
<td>0.3053</td>
<td>9.</td>
</tr>
<tr>
<td>V₁₁</td>
<td>0</td>
<td>0.0355</td>
<td>0.0132</td>
<td>0.0389</td>
<td>0</td>
<td>0.0607</td>
<td>0.0612</td>
<td>0.2096</td>
<td>10.</td>
</tr>
<tr>
<td>Váhy</td>
<td>0.2046</td>
<td>0.2219</td>
<td>0.1207</td>
<td>0.0949</td>
<td>0.1027</td>
<td>0.092</td>
<td>0.1275</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Ore options No. 4 (yield of 0.8499) and No. 7 (yield of 0.7343) received by far the best evaluation. The determined yield of these options was almost double compared to the other types of ore. These ore raw materials can be regarded as significantly better than the other evaluated sorts. Another group of ore raw materials can consist of those ones that were ranked on the 3rd – 6th place, according to the determined value of yield. The differences among these materials are very small again. The remaining evaluated ores can be rated as significantly inferior. The method of the maximization of yield allows sorting the individual ores on the basis of the determined value of total yield, but also allows identifying the optimal one.

4. CONCLUSIONS

The utilization of the methods of multi-criteria evaluation in comparison of ore raw materials appears to be a suitable tool providing a global view of their overall quality. The conducted analysis has clearly shown...
significant differences among the individual monitored materials. If the comparison were conducted only on the basis of isolated criteria, it would not be possible to achieve a complex view. The applied method allows both finding optimal options of ore raw materials and determining the order of all the options. This can be important if the metallurgical company must often compare a large number of offered raw materials. The determined value of yield of ore raw material may also be converted into a point system, which can be used to categorize the ore raw materials.

The outcomes of the evaluation of ore raw materials can be used in long-term strategic decisions related to purchasing and planning. Due to the amount of costs, it is particularly necessary to consider all the aspects in order to find the optimal final solution. The use of mathematical methods for comparison of ore raw materials makes it possible to incorporate a number of entirely different criteria in the evaluation. This aspect fundamentally affects the defined conclusions and evaluations, which are then based on the key factors affecting the blast furnace process. The deviations or deterioration of the quality of ore raw materials can serve as an impulse for a corrective action. Effectively functioning system of evaluation of ore raw materials can serve as a tool for negotiations with the suppliers.

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REFERENCES