

Multi-Criteria selection of technology for processing ore raw materials

E A Gorbatova¹, E A Emelianenko², M V Zaretskii²

¹ All-Russian Scientific-Research Institute of Mineral Resources named after N.M. Fedorovsky, 31, Staromonetny St., Moscow, 119017, Russia

² Nosov Magnitogorsk State Technical University, 38, Lenina Av., Magnitogorsk, 455000, Russia

E-mail: m-zaretsky@yandex.ru

Abstract. The development of Computer-Aided Process Planning (CAPP) for the Ore Beneficiation process is considered. The set of parameters to define the quality of the Ore Beneficiation process is identified. The ontological model of CAPP for the Ore Beneficiation process is described. The hybrid choice method of the most appropriate variant of the Ore Beneficiation process based on the Logical Conclusion Rules and the Fuzzy Multi-Criteria Decision Making (MCDM) approach is proposed.

1. Introduction

The efficiency of a modern mining and processing enterprise is determined by the maximum extraction of the valuable components from ore raw materials and compliance with environmental regulations. Valuable components are extracted from the standard ore raw materials, from substandard ore raw materials and waste of mining and processing production. When the extraction of valuable components from substandard raw materials or waste of mining and processing production is inappropriate, it is possible to obtain construction materials during their processing. If any processing of substandard raw materials or production waste is inappropriate, they are stored in compliance with environmental regulations on the surface or in a chemically bound form in the worked-out area in the subsurface.

For selecting, the most appropriate technological process should be created Computer-Aided Process Planning (CAPP). The important component of CAPP is the Decision Support System (DSS). DSS analyzes the totality of the data, and offers the most acceptable variant of the technological process. The selection of the technological process is based on a set of contradicting requirements. The most acceptable technological process is a compromise that satisfies the entire set of requirements. To find a compromise, the authors use the ideas of multi-criteria choice.

One part of the requirements considered may be adequately described in the classical logical conclusion paradigm. Other part of these requirements could be adequately described in the fuzzy logical paradigm only. Therefore, considered DSS is the hybrid system which combines classical and fuzzy logic techniques.

2. Review of the literature

The theoretical basis for the development of CAPP for ore beneficiation processes is the theory of



these processes [1 - 4]. The authors use the principles of the ontological approach to CAPP design described in [5, 6]. Fundamentals of the methodology of Multi-Criteria optimization are explained in [7]. Principles of design of fuzzy expert systems are described in [8]. Design of Hybrid systems Multi-Criteria Decision Making in hydrometallurgy is considered in [9].

3. Formal description of the most important concepts

Let us formulate the most important concepts of the subject area.

A manufacturing process is a sequence of linked operations, which, at every stage, consume one or more resources (employee time, energy, machines, money) to convert inputs (material etc.) into outputs. These outputs then serve as inputs for the next stage until a known goal or end result is reached. A goal is an observable and measurable end result having one or more objectives to be achieved within more or less fixed timeframe.

Let us consider the following as the input flows:

- standard ore raw materials (for the first operation);
- substandard ore raw materials;
- standard product of previous operations;
- substandard product of previous operations;
- waste of mining and processing production.

Let us consider the following as the output flows:

- standard final product (standard copper concentrate or zink concentrate);
- substandard final product (substandard copper concentrate or zink concentrate);
- standard product;
- substandard product;
- waste of mining and processing production.

As the goal the authors consider the achievement of the result, the most appropriate in relation to a set of criteria. This issue will be discussed in detail below.

4. Ontological description of the problem

The formal description of the subject area is based on the ontological paradigm [5, 6].

$Onto = \langle C, Pr, V, I, R, A, D \rangle$.

Here:

- C is the set of classes;
- R is the set of relations;
- Pr is the set of the properties of classes;
- V is the set of the values of properties;
- I is the set of instances of classes;
- A is the set of axioms;
- D is the set of algorithms of conclusion.

Let us consider the following classes:

- C_1 is the class of norms;
- C_2 is the class of standard ore raw materials;
- C_3 is the class of waste of mining and processing production;
- C_4 is the class of operations of floatation;
- C_5 is the class of operations of cleaner floatation;
- C_6 is the class of operations of leaching;
- C_7 is the class of operations of processing without extraction of valuable components;
- C_8 is the class of operations of storage;
- C_9 is the class of manufacturing processes;
- C_{10} is the class of floatation equipment;
- C_{11} is the class of leaching equipment;
- C_{12} is the class of storage equipment.

The set of relations R consists of the following elements:

- is an instance of...;
- is a part of...;
- is consequent...;
- is connected to...;
- is a cause of...;
- has similarity with...

The set of the properties of the class C_1 consists of the following elements:

- $PCuNorm1$ is the minimum copper assay for standard ore raw materials (%);
- $PCuNorm2$ is the minimum copper assay for substandard ore raw materials (%);
- $PZnNorm1$ is the minimum zinc assay for standard ore raw materials (%);
- $PZnNorm2$ is the minimum zinc assay for substandard ore raw materials (%);
- $PSNorm$ is the maximum sulphur assay for all ore raw materials (%);
- $PASNorm$ is the maximum arsenic assay for all ore raw materials (%);
- $dgNorm$ is the minimum grain size for all ore raw materials (μm).

The set of the properties of the class C_2 consists of the following elements:

- PCu is the real copper assay in ore raw materials (%);
- PZn is the real zinc assay in ore raw materials (%);
- PS is the real sulphur assay in ore raw materials (%);
- PAs is the real arsenic assay in ore raw materials (%);
- dg is the real grain size in ore raw materials (μm);
- Ind_Sort is the industrial sort of ore raw materials (4 sorts are considered);
- Str_Text is the structural and textural features of ore raw materials (2 types are considered);

The set of the properties of the class C_3 consists of the following elements:

- PSW is the real sulphur assay in waste (%);
- $PAsW$ is the real arsenic assay in waste (%).

Sets of the properties of classes C_4, C_5, C_6, C_7, C_8 consist of the following elements

- $Equip$ is the list of equipment;
- $Resource$ is the list of resources.

Every instance of class C_9 is a list of instances of classes C_4, C_5, C_6, C_7, C_8 .

Sets of the properties of classes C_{10}, C_{11}, C_{12} consist of one element:

$Param$ is the list of main parameters of the equipment.

5. The system of predicates for logical conclusion

The most important estimates for conclusions must be formulated as a system of predicates:

- $Pr_1 = PCu \geq PCuNorm1$;
- $Pr_2 = PCu \geq PZnNorm1$;
- $Pr_3 = PS > PSNorm$;
- $Pr_4 = As > PAsNorm$;
- $Pr_5 = dg > dgNorm$;
- $Pr_6 = PCu \geq PCuNorm2$;
- $Pr_7 = PZn \geq PZnNorm2$;

To define the industrial sort of ore materials, let us use a system of four predicates:

- $S_1 = Pr_1 \wedge \overline{Pr_2}$;
- $S_2 = \overline{Pr_1} \wedge Pr_2$;
- $S_3 = \overline{Pr_1} \wedge \overline{Pr_2} \wedge Pr_3$;
- $S_4 = \overline{Pr_1} \wedge Pr_2$.

The variant when all these predicates are equal to False is impossible for our practice. When the predicate number i is equal to "true", ore materials have sort number i .

To define structural and textural features of ore materials, let us use a predicate:

$$T = \overline{Pr}_3 \wedge (S_1 \vee (\overline{Pr}_1 \wedge \overline{Pr}_2) \vee S_4).$$

6. The algorithm of conclusion based on fuzzy logic

It is impossible choose the method of processing of ore materials using classical logic only. In many cases one must use an intuitive choice. Fuzzy logic approaches give us procedures of using expert opinions.

There are many methods of Fuzzy Multi-Criteria Decision Making. Let us use a well-known method Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) which is extended for decision-making with fuzzy data [10].

Let us consider four criteria for estimation of processing of ore raw materials:

ecology;

economy;

technology;

rational using of human resources (HR).

There are two kinds of criteria. Cost criteria are used when the variant with smallest rating is the best. Benefit criteria are used when the variant with the largest rating is the best. Let us assume that economy and technology criteria belong to the set of benefit criteria, ecology and HR criteria belong to the set of cost criteria.

The decision group consists of $K = 3$ experts. Let us assume that all experts have the same qualification. Experts give estimates of all variants by all criteria using linguistic variables. Every linguistic variable is represented by a triangular fuzzy number which is a triplet (a_1, a_2, a_3) , $a_1 \leq a_2 \leq a_3$. Let us use the set of five linguistic variables (Table 1).

Table 1. Linguistic variables

Linguistic variable	Fuzzy number
Very Low (VL)	(1, 1, 3),
Low (L)	(1, 3, 5)
Medium (M)	(3, 5, 7)
High (H)	(5, 7, 9)
Very High (VH)	(7, 9, 9)

Next, let us consider the example of the use of this algorithm. Let us consider two alternatives. The first alternative is the extraction of valuable component from substandard raw materials. The second alternative is the processing of substandard raw materials to obtain construction materials.

First of all experts define weights of criteria (Table 2).

Table 2. Weights of criteria

Expert	Ecology	Economy	Technology	HR
Expert 1	H	H	M	M
Expert 2	VH	H	M	L
Expert 3	VH	VH	H	M

Then experts define ratings of alternatives (Table 3) and the program system calculates aggregated weights of criteria (Table 4), replaces the linguistic variables by corresponding fuzzy numbers, calculates aggregated weights of criteria (Table 4) and aggregated fuzzy decision matrix (Table 5).

Table 3. Ratings of alternatives

	Alternative 1			Alternative 2		
	Expert 1	Expert 2	Expert 3	Expert 1	Expert 2	Expert 3
Ecology	H	M	H	H	VH	H
Economy	VH	VH	H	M	L	L
Technology	VH	H	H	H	M	M
HR	H	VH	H	L	L	L

Table 4. Aggregated weights of criteria

Ecology	Economy	Technology	HR
(5, 8.33, 9)	(5, 7.67, 9)	(3, 5.67, 9)	(1, 4.33, 9)

Table 5. Aggregated fuzzy decision matrix

	Alternative 1	Alternative 2
Ecology	(3, 6.33, 9)	(5, 7.67, 9)
Economy	(5, 8.33, 9)	(1, 3.67, 7)
Technology	(5, 7.67, 9)	(3, 5.67, 9)
HR	(5, 7.67, 9)	(1, 3, 5)

The program system finds the Fuzzy Positive Ideal Solution (FPIS) and Fuzzy Negative Ideal Solution (FNIS). These ideal solutions could not be achieved in reality. The best alternative must be the closest to the FPIS and the furthest from the FNIS. The system calculates distances from FPIS and from FNIS for every criterion for both alternatives (Table 6). Then it calculates $d_i^*, i = 1,2$ — the sum of distances of both alternatives from the FPIS and $d_i^-, i = 1,2$ — the sum of distances of both alternatives from the FNIS.

Table 6. Distances from FPIS and FNIS for alternatives

	D FPIS-Alt1	D FPIS-Alt2	D FNIS-Alt1	D FNIS-Alt2
Ecology	5.14	5.76	4.43	2.34
Economy	3.76	6.05	6.30	4.01
Technology	4.87	5.58	5.14	4.85
HR	6.33	5.07	0.79	4.05

The system calculates distances from FPIS and from FNIS for every criterion for both alternatives. Then it calculates $d_i^*, i = 1,2$ — the sum of distances of both alternatives from the FPIS and $d_i^-, i = 1,2$ — the sum of distances of both alternatives from the FNIS. Then the system calculates the closeness coefficient for every alternative: $CC_i = \frac{d_i^-}{d_i^- + d_i^*}$.

The alternative with the highest closeness coefficient is the closest to the FPIS and the farthest from FNIS. Let us assume it is the best alternative.

In our case, $CC_1 = 0.45, CC_2 = 0.40$. So the system chooses the first alternative.

7. The Hybrid Algorithm of Multi-Criteria Decision Making

The Hybrid algorithm consists of some steps:

1. getting values of predicates Pr_1, \dots, Pr_7 , go to step 2;
2. getting value of predicate T (this value defines details of processing), go to step 3;
3. getting values of predicates S_1, \dots, S_4 :
 - 3.1 if $S_1 = True$ — the main valuable component is copper, go to step 4;
 - 3.2 if $S_2 = True$ — main valuable components are copper and zinc, go to step 4;
 - 3.3 if $S_4 = True$ — the main valuable component is zinc, go to step 4;
 - 3.4 If $S_3 = True$ — there are no main valuable components, ore raw materials are substandard, go to step 6;
4. if $Pr_5 = False$ go to step 6, otherwise go to step 5;
5. floatation, output flow consists of waste, go to step 6;
6. if $(Pr_6 \vee Pr_7) = True$ go to step 7, otherwise go to step 8;
7. fuzzy choice between cleaner flotation and leaching, chosen operation, output flow consists of waste, go to step 8;
8. fuzzy choice of operation with substandard materials: if the processing to obtain construction materials is chosen, go to step 9, otherwise go to step 10;
9. the processing to obtain construction materials, go to step 10;
10. final placing of wastes.

This algorithm determines the sequence of extraction of valuable components. After the extraction of valuable components, this algorithm determines the possibility of processing of substandard materials to obtain construction materials. At the final pass, this algorithm determines the placing of wastes, which could not be processed by any means.

8. Conclusion

A software implementation of the hybrid system of choice of the beneficiation process of ore raw materials has been created. This software uses conclusion rules of the classic logic. Also this software takes into account the intuition and experience of the specialists. It is possible because of using the fuzzy logic paradigm.

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