Selection of lead-zinc flotation circuit design by applying WASPAS method with single-valued neutrosophic set

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In this paper, selection of adequate circuit design of lead-zinc froth flotation, which has a significant impact on the processing costs and useful minerals utilization, is considered. This complex selection problem can be adequately presented as an MCDM problem. Three different circuit design schemes are considered: Sequential Selective Pn-Zn flotation, Collective-Sequential Selective Pn-Zn flotation, Collective Pn-Zn flotation. An approach for solving complex decision-making problems based on the use of WASPAS method and single-valued neutrosophic sets, namely WASPAS-SVNS, is proposed. The efficiency and usability of the proposed approach are considered on the example of a lead-zinc flotation scheme selection problem.

***Key words**: lead-zinc flotation, multi-criteria decision making, WASPAS-SVNS, neutrosophic set.*

1. Introduction

Valuable minerals usually occur in low concentrations in ores, as part of supporting less valuable or valueless substances. Not so rare ore contains more types of valuable minerals.

As an example of metals that often occur together in ores can be specified copper, lead, zinc, silver and gold, where lead (Pb) and zinc (Zn) can particularly be highlighted as metals whose minerals usually occur together in ores. To further processing these minerals, it is usually necessary to make their separation, where the froth flotation is commonly used in for beneficiation of valuable minerals.

The froth flotation is a very complex physicochemical separation process that utilizes the difference in surface properties of the valuable minerals and unwanted gangue minerals. Such differences in mineral properties between the minerals within the flotation pulp become apparent after conditioning with suitable reagents like depressant, activators, promoters, collectors, etc. The attachment of valuable minerals to air bubbles is the most important mechanism and represents the majority of the particles that are recovered as a concentrate (Kumar et al. 2013, Wills and Napier-Munn, 2006).

The separation of Pb and Zn in froth flotation, as well as its efficiency, are discussed in numerous studies, such as Chen and Xiao (2016), Mikhlin et al. (2016), Dehghan and Dianati (2015), Ran et al. (2014) and Huang et al. (2013). Many different characteristics of the froth flotation process, usually some aspects related to the complex physicochemical reactions and kinetics of the milled ore particles, were considered in these studies.

However, the number of papers that treated Pb-Zn flotation process as MCDM problem is minor compared to the number of papers devoted to physicochemical reactions and kinetics in the froth flotation process. As an example of these rare papers, Kostovic and Gligoric (2015), and Savic et al. (2015) can be mentioned.

The number of papers that consider various decision-making problems related to extraction of the valuable minerals from the MCDM standpoint is slightly larger, and Baral et al. (2014), Rahimdel and Ataei (2014), Chakraborty and Chakraborty (2012) and so on can be mentioned as some of such papers. Guria et al. (2005), Stanujkic (2013) and Stanujkic et al. (2013) considered some aspects of flotation circuit design selection from the MCDM standpoint.

The relatively low prices of raw metals, as well as not so rarely significant variations of their prices on the stock market, often require the use of the beneficiation process that ensures high technological and economic efficiency, particularly when poorer ores are processed. For these reasons, as well as the specific characteristic of certain ores, several technological schemes of Pb-Zn froth flotation, with different technological and economic efficiency, were proposed.

Higher technological efficiency should lead to higher economic efficiency. However, froth flotation process is very complex so that the increasing of technological efficiency does not always result in the increasing of

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economic efficiency. Additionally, investment and processing costs should also be taken into account when selecting the appropriate of Pb-Zn froth flotation circuit design. In order to solve this problem in an efficient way, a framework of the multi-criteria decision making can be applied.

During the recent years, researchers have applied a lot of the efforts to take into account different aspects of the complex real-life problems applying multi-criteria decision-making frameworks, such as Morselli (2015), Filip et al. (2014) and Urbaniec (2015). Another direction of the research is incorporation of the vagueness of the initial information in the cases of the solution of the complex nature practical problems by multi-criteria decision making (MCDM) methods. Nowadays, the novel extensions are formulated for the original crisp MCDM methods applying the different types of the fuzzy sets in order to incorporate the indeterminacy of the initial information considered at the real world practical decision problems.

A brief history of the one MCDM method, namely WASPAS, which would be the basis for the solution of the most appropriate Pb-Zn flotation circuit design, is considered in more detail. Zavadskas et al. (2012) proposed and originally described Weighted Aggregated Sum Product Assessment (WASPAS) method. This method aggregates the Weighted Sum Model (WSM) and the Weighted Product Model (WPM) in order to construct a universal decision-making strategy. The first attempt to extend the original crisp WASPAS method for MCDM problems that deal with the uncertainty of the initial information was performed in 2014 (Zavadskas et al. 2014). The proposed extension, namely WASPAS-IVIF, was formulated under an environment of the interval-valued intuitionistic fuzzy numbers. Recently, a multiple novel attribute Weighted Aggregated Sum Product Assessment method with the grey attributes scores, namely WASPAS-G, was proposed in Zavadskas et al. (2015b). The proposed novel technique is governed by grey number algebra, which enables dealing with the imprecise information and can provide enhanced accuracy in the decision-making process. Turskis et al. (2015) proposed a fuzzy multi-attribute performance measurement (MAPM) framework, which incorporates the application of the novel Weighted Aggregated Sum-Product Assessment method with Fuzzy values (WASPAS-F) and Analytical Hierarchy Process (AHP). This approach allows dealing with qualitative attributes, which are usually accompanied by ambiguities and vagueness, in a natural way. The WASPAS method is extended for group decision making with interval type-2 fuzzy sets (Keshavarz Ghorabaee et al. 2015). A new extension of WASPAS method, namely WASPAS-SVNS was also proposed by Zavadskas et al. (2015) in the current year. This new approach is formulated under an environment of the single-valued neutrosophic set. The considered neutrosophic set provides the means to represent and model the vagueness of the initial information explicitly.

Therefore, this manuscript is organized as follows: Section 2 presents an approach for the evaluation of Pb-Zn flotation circuit designs. The main definitions the neutrosophic sets are discussed in Section 3 and Section 4 presents an extension of the WASPAS method adapted for the use of the single-valued neutrosophic set. In Section 5, an example is considered in order to verify the proposed approach. Finally, Section 6 presents the conclusions.

2. Evaluation of Pb-Zn flotation circuit designs

In some ore deposits, Galena ore (PbS) is usually found together with Sphalerite ore (ZnS) in sulfide mineral. Before a pyrometallurgical separation of lead (Pb) and zinc (Zn) from sulphide ores it is necessary to increase the concentration of the valuable minerals in ore concentrate, whereby the beneficiation is usually carried out by using froth flotation.

During the flotation process, it is necessary to achieve some conflicting requirements such as: as large as possible utilization of valuable minerals, the best possible separation of Pb and Zn minerals, a larger amount of concentrate, lower investment and processing costs, etc. In order to achieve such conflicting requirements, various flotation circuit designs have been proposed, of which the following can be mentioned as frequently used:

- the Sequential Selective Pn-Zn Flotation (SSF),
- the Collective-Sequential Selective Pn-Zn Flotation (CSSF), and
- the Collective Selective Pn-Zn Flotation (CSF).

The above-mentioned flotation circuit designs are shown in Figures 1 to 3.

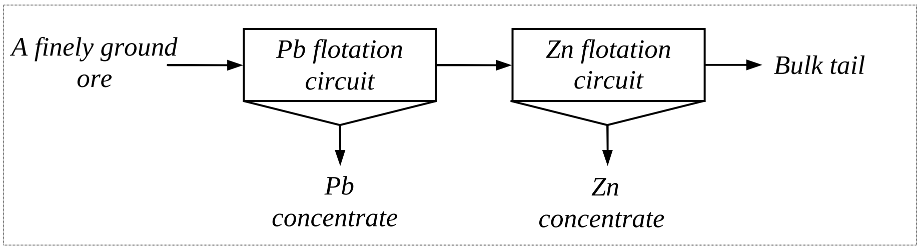

Fig. 1. The Sequential Selective Pn-Zn flotation.

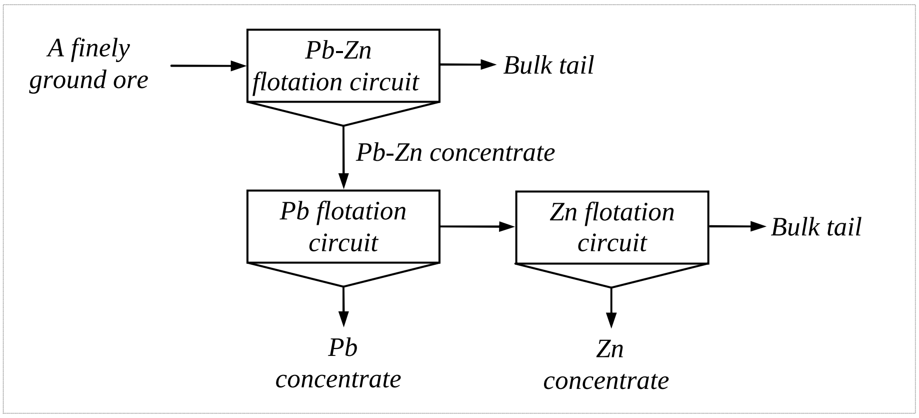

Fig. 2. The Collective-Sequential Selective Pn-Zn flotation.

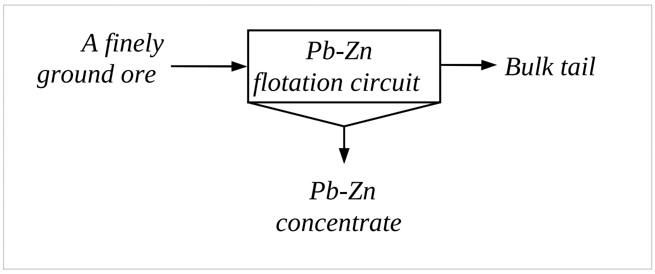

Fig. 3. The Collective Pn-Zn flotation.

From the above, it is evident that selection of an adequate Pb-Zn flotation circuit design can be identified as MCDM problem.

Due to the complexity of the froth flotation separation process, based on the opinions of domain experts, the following criteria are proposed for evaluation and selection of the most appropriate circuit design of a Pb-Zn flotation:

- Milling Costs - MiC,
- Capital Investment Costs - CIC,
- Flotation Reagents Costs - FRC,
- Ecological Costs - EC,
- Maintenance Costs - MaC,
- Utilization of Lead - UL,
- Utilization of Zinc - UZ,
- Lead concentrate Processing Costs - LPC,
- Zinc concentrate Processing Costs - ZPC.

Criteria above are applied to formulate MCDM problem.

3. Neutrosophic sets

Smarandache (1999) presented the new concept of the application of the neutrosophic sets for the modeling real world problems. In this section, the main operations of the neutrosophic set algebra, which are the basics of the proposed extension, are presented.

Definition 1. Let X be the space of the modeled objects of the problem under consideration and $x \in X$. A neutrosophic set A in X is governed by three functions: truth-membership function $T_A(x)$, an indeterminacy-membership function $I_A(x)$ and falsity-membership function $F_A(x)$. These governing functions $T_A(x)$, $I_A(x)$ and $F_A(x)$ are defined by real standard or real non-standard subsets of $\left]0^-,1^+\right[$. That is $T_A(x): X \to \left]0^-,1^+\right[$, $I_A(x): X \to \left]0^-,1^+\right[$ and $F_A(x): X \to \left]0^-,1^+\right[$. In contrary to the application of the other fuzzy sets, for the case of the neutrosophic sets, any restriction on the sum of $T_A(x), I_A(x)$ and $F_A(x)$ is not introduced, so $0^- \leq \sup T_A(x) + \sup I_A(x) + \sup F_A(x) \leq 3^+$.

Definition 2. A single-valued neutrosophic set (SVNS) has been defined as follows. In fact, this set is a simplified version of the neutrosophic set. The elements of the SVNS $\tilde{N} \subset X$ can be expressed as

$$\tilde{N} = \left\{\left\langle x, T_{\tilde{N}}(x), I_{\tilde{N}}(x), F_{\tilde{N}}(x)\right\rangle : x \in X\right\} \tag{1}$$

here $T_{\tilde{N}}(x): X \to [0,1]$, $I_{\tilde{N}}(x): X \to [0,1]$ and $F_{\tilde{N}}(x): X \to [0,1]$ with $0 \leq T_{\tilde{N}}(x) + I_{\tilde{N}}(x) + F_{\tilde{N}}(x) \leq 3$ or all $\tilde{N} \subset X$. The values $T_{\tilde{N}}(x)$, $I_{\tilde{N}}(x)$ and $F_{\tilde{N}}(x)$ correspond to truth-membership degree, the indeterminacy-membership degree and the falsity-membership degree of x to $\tilde{N}$, respectively. Since each SVNS contains just one element, a single-valued neutrosophic number (SVNN) is expressed by $\tilde{N}_A = (t_A, i_A, f_A)$ where $t_A, i_A, f_A \in [0,1]$ and $0 \leq t_A + i_A + f_A \leq 3$.

Definition 3. If $\tilde{N}_1 = (t_1, i_1, f_1)$ and $\tilde{N}_2 = (t_2, i_2, f_2)$ are two SVNNs, then the summation of the $\tilde{N}_1$ and $\tilde{N}_2$ can be performed by the following expression

$$\tilde{N}_1 \oplus \tilde{N}_2 = \left(t_1 + t_2 - t_1 t_2, i_1 i_2, f_1 f_2\right) \tag{2}$$

Definition 4. If $\tilde{N}_1 = (t_1, i_1, f_1)$ and $\tilde{N}_2 = (t_2, i_2, f_2)$ are two SVNNs, then multiplication of the $\tilde{N}_1$ and $\tilde{N}_2$ can be calculated by the following expression

$$\tilde{N}_1 \otimes \tilde{N}_2 = \left(t_1 t_2, i_1 + i_2 - i_1 i_2, f_1 + f_2 - f_1 f_2\right) \tag{3}$$

Definition 5. If $\tilde{N}_1 = (t_1, i_1, f_1)$ is an SVNN and $\lambda \in \Re$ is an arbitrary positive real number, then multiplication of the neutrosophic and real numbers can be expressed as

$$\lambda \tilde{N}_1 = \left(1 - (1 - t_1)^{\lambda}, i_1^{\lambda}, f_1^{\lambda}\right), \lambda > 0 \tag{4}$$

Definition 6. If $\tilde{N}_1 = (t_1, i_1, f_1)$ is an SVNN and $\lambda \in \Re$ is an arbitrary positive real number, then power function of these variables can be constructed as follows

$$\tilde{N}_1^{\lambda} = \left(t_1^{\lambda}, 1 - (1 - i_1)^{\lambda}, 1 - (1 - f_1)^{\lambda}\right), \lambda > 0 \tag{5}$$

Definition 7. If $\tilde{N}_1 = (t_1, i_1, f_1)$ is an SVNN, then the complementary component is defined in the following way

$$\tilde{N}_1^{\,c} = \left(f_1, 1 - i_1, t_1\right) \tag{6}$$

Definition 8. If $\tilde{N}_A = (t_A, i_A, f_A)$ is an SVNN, a score function is defined as follows

$$S\left(\tilde{N}_A\right) = \frac{3 + t_A - 2i_A - f_A}{4} \tag{7}$$

where $S\left(\tilde{N}_A\right) \in [0,1]$. This score function has the same range as all functions applied in the definition of the neutrosophic sets (Bausys *et al*. 2015).

Definition 9. Let $\tilde{N}_1$ and $\tilde{N}_2$ be any two SVNNs. Therefore, if $S\left(\tilde{N}_1\right) < S\left(\tilde{N}_2\right)$ then $\tilde{N}_1$ is smaller than $\tilde{N}_2$, $\tilde{N}_1 < \tilde{N}_2$.

4. A WASPAS method by single-valued neutrosophic set

Originally, the method of the multicriteria decision making, namely a weighted aggregated sum product assessment (WASPAS) approach, was presented by Zavadskas et al. (2012). The novel extension of this method, namely WASPAS-SVNS, was formulated on the basis of the framework of the single-valued neutrosophic set and presented in Zavadskas et al. (2015a). The main ideas of the applied method WASPAS-SVNS, by which the solution of the considered MCDM is performed, can be presented as follows.

Step 1. In this step, a decision-making matrix X is constructed. The elements of this matrix represent the ratings of the alternatives with respect to the considered options. These elements can be expressed by $x_{ij}, i = 1,2,...,m; j = 1,2,...,n$, which is the ratings of the alternative *i* with respect to the criterion *j*. So the aggregated decision matrix can be expressed as

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \tag{8}$$

Step 2. Normalization of the decision matrix X is calculated on the basis of the vector normalization strategy, which can be expressed as follows

$$\tilde{x}_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} \left(x_{ij}\right)^2}} \tag{9}$$

Step 3. At this step, conversion of the normalized aggregated decision matrix $\tilde{X}$ in the crisp form, obtained in the previous step, to the neutrosophic numbers is performed. Therefore, the neutrosophic aggregated decision matrix $\tilde{X}^n$ is calculated. For this conversion, the relationships between normalized terms of the alternatives and single-valued neutrosophic numbers are applied. These conversion grades are defined applying linguistic expressions and are presented in Table 1.

Tab. 1. Neutrosophication grades to express the importance of the alternatives.

Crisp normalized terms	**SVNNs**
Extremely good (EG) / 1.0	(1.00, 0.00, 0.00)
Very very good (VVG) / 0.9	(0.90, 0.10, 0.10)
Very good (VG)/ 0.8	(0.80, 0.15, 0.20)
Good (G) / 0.7	(0.70, 0.25, 0.30)
Medium good (MG) / 0.6	(0.60, 0.35, 0.40)
Medium (M) / 0.5	(0.50, 0.50, 0.50)
Medium bad (MB) / 0.4	(0.40, 0.65, 0.60)
Bad (B) / 0.3	(0.30, 0.75, 0.70)
Very bad (VB) / 0.2	(0.20, 0.85, 0.80)
Very very bad (VVB) / 0.1	(0.10, 0.90, 0.90)
Extremely bad (EB) / 0.0	(0.00, 1.00, 1.00)

Step 4. Applying the first decision-making strategy of the WASPAS-SVNS method, the total relative importance of the alternative *i* is calculated as follows

$$\tilde{Q}_i^{(1)} = \sum_{j=1}^{L_{max}} \tilde{x}_{+ij}^{n} \cdot w_{+j}^{n} + \left(\sum_{j=1}^{L_{min}} \tilde{x}_{-ij}^{n} \cdot w_{-j}^{n}\right)^{c} \tag{10}$$

where $\tilde{x}^n_{+ij}$ and w^n_{+j} values correspond to the criteria, which have to be maximized, and $\tilde{x}^n_{-ij}$ and w^n_{-j} values correspond to the criteria, which have to be minimized.

Step 5. Applying the second decision-making strategy, which is incorporated into WASPAS-SVNS methodology, the product total relative importance of the alternative *i* is governed by the following equation:

$$\tilde{Q}_i^{(2)} = \prod\nolimits_{j=1}^{L_{max}} \left(\tilde{x}^n_{+ij}\right)^{w^n_{+j}} \cdot \left(\prod\nolimits_{j=1}^{L_{min}} \left(\tilde{x}^n_{-ij}\right)^{w^n_{-j}}\right)^c \tag{11}$$

The same definition of the equation components is applied as in the previous equation (10).

Step 6. A common generalized criteria that incorporate the ranking results obtained by both decision strategies, of the WASPAS-SVNS approach, is calculated and has the following form:

$$\tilde{Q}_i = 0.5\tilde{Q}_i^{(1)} + 0.5\tilde{Q}_i^{(2)} \tag{12}$$

Step 7. In the last step, the score function $S\left(\tilde{Q}_i\right)$ is applied to perform the backward conversion to crisp values and the final rankings of the alternatives are calculated and ordered in the descending way of the $\tilde{Q}_i$.

5. Numerical example

To highlight the proposed approach, an example of selecting the most appropriate Pb-Zn flotation scheme is considered. The considered problem has been solved by WASPAS-SVNS method in order to demonstrate the numerical efficiency of the proposed MCDM approach.

For beneficiation of a Pb-Zn ore three previously discussed circuit designs, SSF, CSSF, and CSF, are evaluated on the basis of evaluation criteria proposed in Section 2.

The ratings of considered alternatives, denoted as A_1, A_2 and A_3, obtained from an expert are shown in Table 2. The weight of evaluation criteria, obtained by the SWARA method (Kersuliene *et al.* 2010), are also shown in Table 2.

Tab. 2. Initial decision-making matrix.

Criteria	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
	MiC	**CIC**	**FRC**	**EC**	**MaC**	**UL**	**UZ**	**LPC**	**ZPC**
w_i	0.18 min	0.08 min	0.15 min	0.05 min	0.05 min	0.20 max	0.20 max	0.04 min	0.04 min
A_1	1	1	1.05	1	1	0.95	0.95	1	1
A_2	0.9	1.15	1.1	1.2	1.05	0.93	0.93	1	1
A_3	0.8	0.9	0.7	0.8	0.95	0.96	0.96	1.1	1.1

The aggregated decision matrix, obtained after neutrosophic conversion, is presented in Table 3.

Tab. 3. The aggregated decision matrix $\tilde{X}^n$ after neutrosophication step.

Criteria	**Alternatives**		
	A_1	A_2	A_3
C_1 **min**	(0.6389, 0.3111, 0.3611)	(0.5750, 0.3875, 0.4250)	(0.5111, 0.4833, 0.4889)
C_2 **min**	(0.5650, 0.4025, 0.4350)	(0.6498, 0.3002, 0.3502)	(0.5085, 0.4872, 0.4915)
C_3 **min**	(0.6272, 0.3228, 0.3728)	(0.6571, 0.2929, 0.3429)	(0.4181, 0.6228, 0.5819)
C_4 **min**	(0.5698, 0.3953, 0.4302)	(0.6838, 0.2662, 0.3162)	(0.4558, 0.5662, 0.5442)
C_5 **min**	(0.5769, 0.3847, 0.4231)	(0.6057, 0.3443, 0.3943)	(0.5480, 0.4280, 0.4520)
C_6 **max**	(0.5793, 0.3810, 0.4207)	(0.5671, 0.3993, 0.4329)	(0.5854, 0.3719, 0.4146)
C_7 **max**	(0.5793, 0.3810, 0.4207)	(0.5671, 0.3993, 0.4329)	(0.5854, 0.3719, 0.4146)
C_8 **min**	(0. 5581, 0.4128, 0.4419)	(0.5581, 0.4128, 0.4419)	(0.6140, 0.3360, 0.3860)
C_9 **min**	(0. 5581, 0.4128, 0.4419)	(0.5581, 0.4128, 0.4419)	(0.6140, 0.3360, 0.3860)

The numerical results, representing the application of the steps 4-7, are shown in Table 4. The rankings of the alternatives are performed by the score of functions of WASPAS-SVNS method (Eq. 7). It is not difficult to make the conclusion that the most preferred alternative is A_3. Therefore, the most efficient is CSF circuit design scheme.

Tab. 4. Numerical results obtained by WASPAS-SVNS.

	Alternatives		
	$\boldsymbol{A_1}$	$\boldsymbol{A_2}$	$\boldsymbol{A_3}$
$\tilde{Q}^{(1)}$	(0.6659, 0.3155, 0.2909)	(0.6643, 0.3205, 0.2964)	(0.7530, 0.2332, 0.2311)
$\tilde{Q}^{(2)}$	(0.4480, 0.5382, 0.5520)	(0.4430, 0.5457, 0.5570)	(0.4603, 0.5195, 0.5397)
$\tilde{Q}$	(0.5705, 0.4121, 0.4173)	(0.5676, 0.4182, 0.4225)	(0.6349, 0.3480, 0.3547)
$S(\tilde{Q})$	0.5823	0.5772	0.646
Rank	2	3	1

6. Conclusions

Selection of adequate circuit design of lead-zinc froth flotation can have a significant impact on the processing costs and useful mineral utilization. This complex selection problem can be adequately presented as an MCDM problem that involves evaluation based on multiple, mutually opposed, criteria. For the assessment of three lead-zinc froth flotation circuit design schemes are implemented. The solution of that decision-making problem is performed by a novel extension, namely WASPAS-SVNS. This approach WASPAS-SVNS is constructed on the basis of the environment of the single-valued neutrosophic set that enables to construct independent functions for the truth-membership degree, the indeterminacy-membership degree, and the falsity-membership degree. Or, in other words, the proposed technique allows incorporating the vagueness of initial information into the considered models for the assessment of lead-zinc froth flotation circuit schemes.

Finally, the considered example confirms the usability and efficiency of the proposed WASPAS-SVNS extension for selecting the most appropriate lead-zinc flotation circuit design. Among the considered circuit design schemes, the most efficient is collective Pn-Zn flotation circuit design scheme. It is worth to point out that application of the MCDM framework allows solving complex engineering problems in the most efficient way.

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