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An approach based on Fuzzy Best-Worst method for sustainable evaluation of mining industries

Introduction

There are some frequently used phrases in this paper whose acronyms will be used as listed in Table 1.

Table 1. Acronyms of frequently used phrases

Tabela 1. Akronimy często używanych zwrotów

Phrase	Acronym
Best-Worst Method	BWM
Fuzzy Best-Worst Method	FBWM
Analytic Hierarchy Process	AHP
Multi-Criteria Decision Making	MCDM
Sangan Iron Ore Mines	SIOM

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The concept of sustainable development and attention to environmental characteristics dates back to the early 1970s. Sustainable development was first defined in 1980 by the International Union for Conservation of Nature and Natural Resources (Asr et al. 2019). The organization uses the term sustainable development in cases that not only do not threaten nature and but also supports it (Asr et al. 2019). In 1992, at a meeting organized by the World Commission on Environment and Development in Rio de Janeiro, Brazil, the global, national and local requirements were presented for more sustainable life on Earth. In addition to the environmental aspects, the commission also included social and economic facets in the definition of sustainable development (Temple 1992). Considering the pervasive applications of sustainability, giving a comprehensive and uniform definition of sustainable development covering all playing fields is rather problematic (Nuong et al. 2011). According to the Brundtland Commission (1987), sustainability is typically considered as a process that "meets the existing needs, regardless of the future generations' ability to meet their needs" (Asr et al. 2019). Sustainable development can be defined as a developmental program that, in addition to improving the current generation's life, pays attention to the future generations (Dernbach 1998; Cerin 2006). Thus, sustainable development can be stated to have a general conception of social, economic, cultural, environmental and other human needs. It is worth to mention that inclusiveness tends to attract more sustainability (Rajaram et al. 2005; Botin 2009).

The beginning of interest in applying sustainable development in mining industry was at the United Nations Conference in Rio de Janeiro, Brazil in 1992 (Rahmanpour and Osanloo 2017). Since then, various definitions of sustainable mining and its application have been presented in the mining industry. For example, Allan (Allan 1995) introduces sustainable mining, in cases where utilizing minerals is not greater than the capacity of new sources, acceptable alternatives or recycling. However, according to some researchers, because of the limited lifetime of mines and the unlimited dependence of humankind on non-renewable resources, this activity cannot be regarded as an entirely sustainable activity (Crowson 1998; Rajaram et al. 2005; Worrall et al. 2009).

But some others believe that mining can be considered a long-term sustainable activity (Learmont 1997), and with optimal management, this activity can provide sustainable opportunities for economic growth and development (Basu and Kumar 2004). With a more comprehensive view, the mineral industry can be considered as a network of long-term value chains that begins with the exploration of mineral resources followed by designing, constructing, exploiting over years and decades (McLellan et al. 2009). At each stage of the mining industry development, undesirable environmental and social impacts can be issued and thus, there must be a balance between the long-term economic benefits and the resulting harmful environmental and social impacts (Pimentel et al. 2016). Operating mines requires high capital costs and so efficiency in operations and budget allocation plays an important role. It is believed that increasing capital and operational costs have a significant impact on the productivity of mines (Lala et al. 2016). Accordingly to achieve sustainable objectives in mines, the decision-making process should be built on economic analysis besides environmental and social perspectives.

Hence, developing an appropriate method for evaluating mines operations concerning the economic, environmental and social criteria is of high importance. There is a hierarchical structure between the objective functions (performance evaluation of mines), criteria, sub-criteria and alternatives (mines). Since the interdependence between the criteria is negligible, FBWM is used in the proposed approach for weighting the criteria and sub-criteria. One of the problems in the evaluation process is the paired comparisons between the criteria because by increasing the number of criteria and sub-criteria, this process becomes computationally extensive and the probability of error in pairwise comparison and consistency between them growths.

AHP method, for instance, requires the number of $n(n - 1)/2$ pairwise comparisons to lead to the formation of a pairwise matrix between n, representing the number of criteria; however, BWM method needs the number of just $2n - 3$ pairwise comparisons for this purpose (Rezaei 2015). Therefore, as the "n" increases, BWM obtains a higher superiority in this domain than the other methods that utilize such a matrix. Moreover, this approach makes use of the fuzzy theory in order to include uncertainty in the problem under real world circumstances. The efficiency of this approach can be obtained by conducting a case study in real conditions through expert opinion.

The remaining of this paper is organized as follows. In Section 2 literature review is provided on sustainable development with a focus on analyzing the methodological approaches. Section 3 presents the problem context, proposed approach. The proposed approach is implemented in Section 4 by applying the approach on a real world case in mining industry. Finally, conclusions are drawn and directions are given for future studies in Section 5.

1. Literature review

Today, cooperation and coordination between industries in line with sustainable development is indispensable for many countries (Dubiński 2013). With the advent of sustainable development, common mining has given way to modern mining (Hartman and Mutmansky 2002). Also, concepts such as "Green Mining" and "Responsible mining" have been used as the main pillars of sustainable development in the mining industry. The concept of green mining is used to minimize the environmental damage of mines (Rahmanpour and Osanloo 2017), and in responsible mining, the environmental, social and economic damage caused by mining activity is managed (Jarvie-Eggart 2015).

To develop sustainable mining, it is necessary to evaluate the impact of mining activities on sustainable development indices and prioritize vulnerable sectors (Fonseca et al. 2013; Marnika et al. 2015).

Given the high importance of this topic, numerous studies have been conducted by researchers in this field. Semi-quantitative methods are used to evaluate the impact of mining industry activities on sustainable development indicators, which leads to worthy results, especially on social and environmental issues. One of the most common semi-quantitative methods is the use of a two-dimensional evaluation matrix, which has been widely accepted by researchers in terms of simplicity and usefulness (Ghaedrahmati and Doulati Ardejani 2012).

For the first time, Leopold et al. (2012) developed usage of two-dimensional matrices for environmental threat evaluation. They considered the magnitude and importance of the impact of each activity on each environmental component as the evaluation variables. Schlickmann et al. (2018) used this method for environmental impact assessment in coal mines. Padmala and Jensen (1998) applied The Rapid Impact Assessment Matrix to assess the environmental impact of sand mining. This method assesses environmental impacts without considering project activities as an effective factor in environmental components. The method developed by Folchi (1999), which is based on environmental impact assessment of mining activities to measure environmental impacts, is the most applied in this field and has been commonly used by many researchers. In this method, the affecting mining activities and environmental impacts are carefully evaluated. Kauppinen and Khajehzadeh (2015) used the data envelopment analysis method as a modeling tool for the sustainability of the mine exploration phase.

Multi-criteria decision-making methods have been widely used in the field of mining and in determining sustainable development criteria. Si et al. (2010) used the AHP method to weight the sustainability criteria and evaluate the mines. To test the effectiveness of their approach, they implemented it in a coal mine. A hybrid approach based on AHP, genetic algorithm and fuzzy numbers for measuring the degree of sustainable development in the mining industry was presented by Su et al. (2010). They considered the five criteria namely, mineral resources, economy, society, environment and intelligence as evaluation criteria and implemented it in a mining city in China to evaluate the effectiveness of the proposed model. Govindan et al. (2014) developed a fuzzy DEMATEL-based framework for evaluating drivers of corporate social responsibility in the mining industry and implemented it in an Indian mining sector to evaluate the effectiveness of the proposed approach. Adibi et al. (2015) presented an optimization model for integrating sustainable development indicators into the design of open pit mining and used the TOPSIS method to rank sustainable indices. Implementation of the proposed approach in a copper mine in Iran indicated the effectiveness of their approach.

Surveys show that MCDM methods are a good way to rank the criteria and evaluate the mining industry. Sitorus et al. (2018) explored the applications and trends of MCDM methods in mining and mineral processing and provided a comprehensive overview. They finally stated that MCDM methods are one of the most widely used and efficient methods in this field.

Therefore, in this paper, using MCDM concepts, a fuzzy BWM based approach to mine evaluation with sustainable development perspective is presented. Moreover, the proposed approach is applied to a mine in Iran.

2. Problem statement and proposed approach

In this section, an integrated approach is developed to evaluate mines from sustainable development perspective. To this end, evaluation criteria are identified based on three dimensions of economic, environmental and social, and are measured by the FBWM. Finally, the performance of the mine is measured per each criterion and its score is then calculated. The proposed step-wise approach is presented as follows.

- **Step 1:** In this step, mine evaluation criteria are extracted and determined based on the studies in related literature and knowledge of the domain experts. Since the mine evaluation is investigated based on sustainable development, the required criteria should cover economic, environmental and social facets of the problem. Assume *n* number of criteria are identified (c_1, c_2, ..., c_B).
- **Step 2:** In this step, the best and worst criteria are selected according to the experts. The best one is the criterion that matters most, and the least important criterion will be selected as the worst criterion. These two criteria are represented by c_B and c_W, respectively.
- **Step 3:** In this step, experts are asked to conduct a paired comparison on the best criterion with other criteria using linguistic terms presented in Table 2. Then by replacing equivalent triangular fuzzy numbers, the Best-to-Others vector is obtained. The obtained fuzzy Best-to-Others vector will be as follows:

$$\tilde{A}_B = (\tilde{a}_{B1}, \tilde{a}_{B2}, ..., \tilde{a}_{Bj}, ..., \tilde{a}_{Bn}) \tag{1}$$

↳ $\tilde{A}_B$ shows the fuzzy Best-to-Others vector; $\tilde{a}_{Bj}$ represents the fuzzy preference of the best criterion c_B over criterion j (j = 1, 2, ..., n). It can be known that $\tilde{a}_{BB} = (1,1,1)$.

Table 2. Linguistic terms for pairwise comparison (Kannan et al. 2020)

Tabela 2. Terminy językowe do porównania parami

Linguistic terms	Triangular fuzzy numbers
Equally importance	(1,1,1)
Weakly importance	(2/3,1,3/2)
Fairly importance	(3/2,2,5/2)
Very importance	(5/2,3,7/2)
Absolutely importance	(7/2,4,9/2)

- **Step 4:** As in Step 3, experts are asked to use the linguistic terms from Table 2 to compare the other criteria with the worst criterion. Then by replacing the equivalent triangular fuzzy numbers, the Others-to-Worst vector is obtained. This vector is as follows.

$$\tilde{A}_W = (\tilde{a}_{1W}, \tilde{a}_{2W}, ..., \tilde{a}_{jW}, ..., \tilde{a}_{nW}) \tag{2}$$

$\tilde{A}_W$ shows the fuzzy Others-to-worst vector; $\tilde{a}_{jW}$ represents the fuzzy preference of the criterion j over the worst criterion c_W, j = 1, 2, ..., n. It can be known that $\tilde{a}_{WW} = (1,1,1)$.

- **Step 5**: In this step, the weight of the criteria is obtained by solving the following fuzzy mathematical model.
  - Parameters

$\tilde{a}_{Bj} = (l_{Bj}, m_{Bj}, u_{Bj})$ Fuzzy preference of the best criterion over the criterion j

$\tilde{a}_{jW} = (l_{jW}, m_{jW}, u_{jW})$ Fuzzy preference of the criterion j over the worst criterion

  - Variables

$\tilde{w}_B = (l_B^w, m_B^w, u_B^w)$ The fuzzy weight of the best criterion

$\tilde{w}_W = (l_W^w, m_W^w, u_W^w)$ The fuzzy weight of the worst criterion

$\tilde{w}_j = (l_j^w, m_j^w, u_j^w)$ The fuzzy weight of the criterion j

  - Mathematical model

$$Min\, Max \left\{ \left| \frac{\tilde{w}_B}{\tilde{w}_j} - \tilde{a}_{Bj} \right|, \left| \frac{\tilde{w}_j}{\tilde{w}_W} - \tilde{a}_{jW} \right| \right\} \tag{3}$$

$$St:$$

$$\sum_{j=1}^{n} R(\tilde{w}_j) = 1$$

$$l_j^w \le m_j^w \le u_j^w$$

$$l_j^w \ge 0$$

$$j = 1, 2, ..., n$$

The weight of the criterion j is represented by $\tilde{w}_j = (l_j^w, m_j^w, u_j^w)$ where, l_j^w, m_j^w and u_j^w are the pessimistic, most possible and optimistic values in triangular fuzzy numbers.

By placing $\tilde{\mu} = Max \left\{ \left| \frac{\tilde{w}_B}{\tilde{w}_j} - \tilde{a}_{Bj} \right|, \left| \frac{\tilde{w}_j}{\tilde{w}_W} - \tilde{a}_{jW} \right| \right\}$ in Eq. (3), a nonlinear model results presented as follows.

$$
\begin{aligned}
& Min\ \tilde{\mu} \\
& St: \\
& \left|\frac{\tilde{w}_B}{\tilde{w}_j} - \tilde{a}_{Bj}\right| \leq \tilde{\mu} \qquad \forall j \\
& \left|\frac{\tilde{w}_j}{\tilde{w}_W} - \tilde{a}_{jW}\right| \leq \tilde{\mu} \qquad \forall j \\
& \sum_j R(\tilde{w}_j) = 1 \\
& l_j^w \leq m_j^w \leq u_j^w \\
& l_j^w \geq 0
\end{aligned} \tag{4}
$$

↳ $\tilde{\mu} = (l^{\mu}, m^{\mu}, u^{\mu})$. Assume $\tilde{\mu}^* = (o^*, o^*, o^*)$ and $o^* \leq l^{\mu}$, so the proposed model would be:

$$
\begin{aligned}
& Min\ \tilde{\mu}^* \\
& St: \\
& \left|\frac{(l_B^w, m_B^w, u_B^w)}{(l_j^w, m_j^w, u_j^w)} - (l_{Bj}, m_{Bj}, u_{Bj})\right| \leq (o^*, o^*, o^*) \qquad \forall j \\
& \left|\frac{(l_j^w, m_j^w, u_j^w)}{(l_W^w, m_W^w, u_W^w)} - (l_{jW}, m_{jW}, u_{jW})\right| \leq (o^*, o^*, o^*) \qquad \forall j \\
& \sum_j R(\tilde{w}_j) = 1 \\
& l_j^w \leq m_j^w \leq u_j^w \\
& l_j^w \geq 0
\end{aligned} \tag{5}
$$

Having implemented the model in the optimization software, the weights of the criteria and $\tilde{\mu}^*$ are determined.

- **Step 6:** In this step, using the consistency index presented in Table 3 and Eq. (6), the consistency ratio is calculated. The closer the consistency ratio to zero, the greater the consistency.

$$
Consistency\ ratio = \frac{o^*}{Consistency\ index} \tag{6}
$$

Table 3. The consistency index for fuzzy BWM (Kannan et al. 2020)

Tabela 3. Wskaźnik spójności dla zbioru rozmytego BWM (*Best-Worst Method*)

Linguistic terms	Equally important	Weakly important	Fairly important	Very important	Absolutely important
$\tilde{A}_{BW}$	(1,1,1)	(2/3,1,3/2)	(3/2,2,5/2)	(5/2,3,7/2)	(7/2,4,9/2)
The consistency index	3	3.8	5.29	6.69	8.04

- **Step 7:** In this step, the mine will be evaluated per each sub-criterion. For this purpose, a questionnaire is provided to the experts and they are asked to rate the mine performance for each sub-criterion using the linguistic terms in Table 4. The average expert opinion will then be considered as the score obtained from the mine evaluation per sub-criterion. Finally, to determine the final score, we calculate the sum of the product of the sub-criteria weight in the evaluated values. These calculations are represented in Eq. (7).

$$Final\ score = \sum_{j=1}^{n} \tilde{w}_j \cdot \tilde{X}_j \tag{7}$$

$\tilde{X}_j = (l_j^X, m_j^X, u_j^X)$ is the mean score obtained from the evaluation of the studied mine for criterion *j*. So we'll have:

$$Fuzzy\ final\ score = \sum_{j=1}^{n} \left(l_j^w, m_j^w, u_j^w\right) \otimes \left(l_j^X, m_j^X, u_j^X\right) = \sum_{j=1}^{n} \left(l_j^w \cdot l_j^X, m_j^w \cdot m_j^X, u_j^w \cdot u_j^X\right) \tag{8}$$

Therefore, the final score of the studied mine is calculated with fuzzy numbers. Now using Eq. (9) performance evaluation is defuzzified (Kannan et al. 2020).

$$Defuzzy\ final\ score = \sum_{j=1}^{n} \frac{(l_j^w \cdot l_j^X) + 4 \cdot (m_j^w \cdot m_j^X) + (u_j^w \cdot u_j^X)}{6} \tag{9}$$

Thus, the final score obtained from the evaluation of the mine performance is calculated from the perspective of sustainable development. In Figure 1, the approach is presented as a stepwise flowchart.

Table 4. Linguistic terms for evaluating alternatives

Tabela 4. Terminy językowe do oceny alternatyw

Linguistic term	Triangular fuzzy number
None	(0,0,0.1)
Very low	(0.1,0.2,0.3)
Low	(0.2,0.3,0.4)
More or less low	(0.3,0.4,0.5)
Medium	(0.4,0.5,0.6)
More or less good	(0.5,0.6,0.7)
Good	(0.6,0.7,0.8)
Very good	(0.7,0.8,0.9)
Excellent	(0.8,0.9,1)

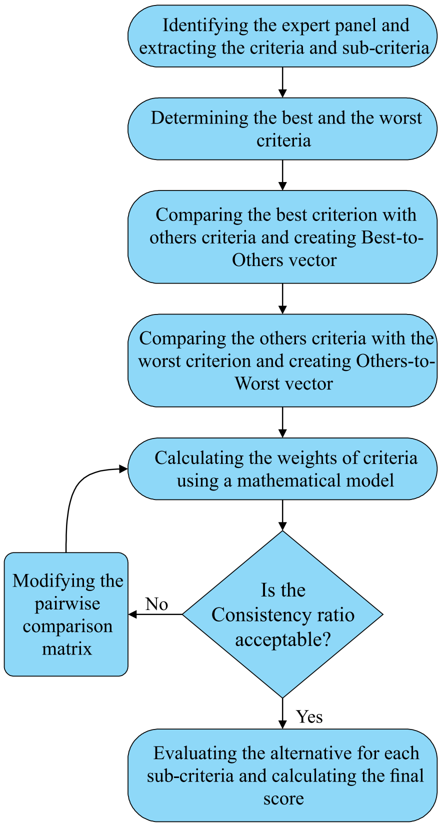

Fig. 1. The structure of proposed approach

Rys. 1. Struktura proponowanego podejścia

3. Case study

To have the proposed approach validated; it is applied to SIOM, one of the largest iron ore deposits in Iran. SIOM is located 300 kilometers southeast of Mashhad, 12 kilometers southwest of Taibat, 40 kilometers southeast of Khawf, 18 kilometers northeast of Sangan and 30 kilometers from the Afghanistan border (Kretschmann and Amiri 2013). The location of this mine is shown in Figure 2.

Fig. 2. SIOM position on Google Earth

Rys. 2. Pozycja SIOM (*Sangan Iron Ore Mines*) na Google Earth

There are many anomalies of iron in this area that are generally divided into three zones: western, central and eastern. Figure 3 shows the relative position of the different SIOM zones (Madankav Engineering Company 2012).

Sangan iron ore is one of the largest iron ore mines in the Middle East that has been named as the largest national project in the eastern part of Iran (IMIDRO 2011). The total

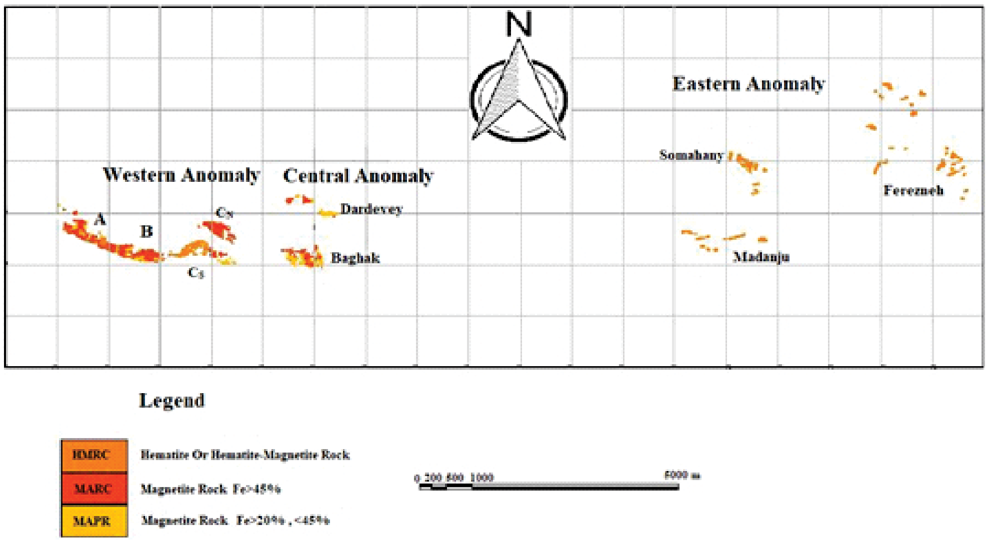

Fig. 3. SIOM Major Zones (Madankav Engineering Company 2012)

Rys. 3. Główne strefy SIOM (*Sangan Iron Ore Mines*)

geological resource of mine is estimated at about 1.2 billion tones, mainly comprising Magnetite with Fe grade of 27–61%. Table 5 shows the last exploration result of SIOM by different zones (Madankav Engineering Company 2012).

Table 5. Mineral resources and reserves of SIOM (Madankav Engineering Company 2012)

Tabela 5. Zasoby i rezerwy mineralne SIOM (*Sangan Iron Ore Mines*)

Zone	Proved (Mt)	Probable (Mt)	Measured (Mt)	Identified (Mt)	Inferred (Mt)	Total (Mt)
Western	160	32	263	139	114	708
Central	238.8	9.9	–	–	71.3	320
Eastern	–	–	–	–	146	146
Total	398.8	41.9	263	139	331.3	1 174

To highlight the SIOM role in the local social and cultural activities, it is worthy to mention that from the very beginning of its operation, SIOM founded a girl's high school in an area of 15,000 square meters in Sangan town to develop the rate of education in the local women community (Kretschmann and Amiri 2013). As it is clear from Figure 4, the

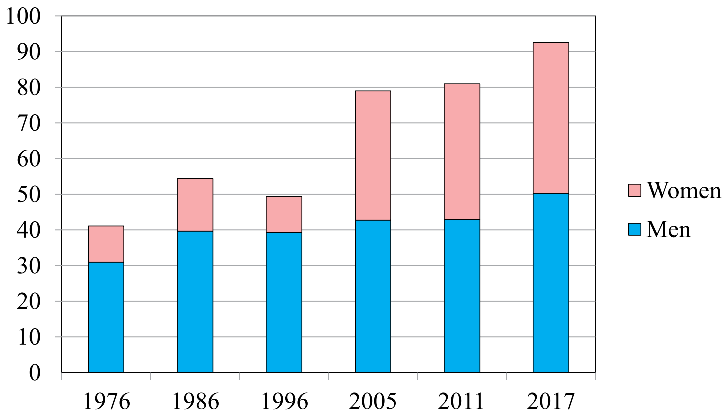

Fig. 4. The percentage of educated adults in Khaf County. The statistics for educated men and women are shown by black and grey columns, respectively (Statistical Center of Iran 2012)

Rys. 4. Procent wykształconych dorosłych w powiecie Khaf. Statystyki dotyczące wykształconych mężczyzn i kobiet są przedstawione odpowiednio przez czarne i szare kolumny

high school has played an important role in educating of woman in the local society since its foundation in 1992. Besides, the SIOM policy is based on increasing the number of its own female staff (Kretschmann and Amiri 2013). Moreover, a technical school was founded in an area of 27,000 square meters at Sangan town entrance in 2001 by the SIOM. The taught disciplines in this school are mining, mechanical, computer, and surveying engineering (Kretschmann and Amiri 2013).

The other noticeable actions made by SIOM for fulfillment of sustainable development goals are including a charity fund establishment in 2004, the construction of three new residential homes for workers, giving help to some local organizations in the Khaf County, providing many employment opportunities which directly resulted in decreasing the rate of criminal activities, improving occupational safety and health, and finally paying more attention to the environmental aspects of mining activities (Kretschmann and Amiri 2013).

The procedure of implementation of the proposed model is as described in the following steps.

- **Step 1:** In this step, by reviewing the literature and referring to experts, the criteria for mine evaluation were extracted from sustainable development viewpoint. For this purpose, a considerable set of criteria was collected by reviewing the articles on sustainability or sustainable mining development and made available to experts. Using brainstorming, the experts selected the appropriate criteria for evaluating the considered mine, which is listed in Table 6. Figure 5 explains more about the criteria and sub-criteria in sustainable development of analyzed mine.
- **Step 2:** In this step, using the experts' opinion, we select the best and worst criteria and sub-criteria as it is shown in Table 7.

Table 6. Criteria and sub-criteria for evaluating SIOM

Tabela 6. Kryteria i podkryteria oceny SIOM (*Sangan Iron Ore Mines*)

Criteria	Sub-criteria	Reference
Economic (EC)	Exploration capacity (EC1)	Shields 2005
	Technological and financial capacity (EC2)	Luo et al. 2019
	Production facility and capability (EC3)	Mina et al. 2014
	Economic benefits (EC4)	Shields 2005
	Rate of return (EC5)	Zanbak and Karahan 2005
	Use of energy (EC6)	Ford 2004; Shields 2005
	Applying research and development (EC7)	Shields 2005
Environmental (EN)	Environmental management systems (EN1)	Zanbak and Karahan 2005
	Waste management (EN2)	Zanbak and Karahan 2005; Amirshenava and Osanloo 2018
	Air emissions (EN3)	Ford 2004; Zanbak and Karahan 2005; Amirshenava and Osanloo 2018; Amirshenava and Osanloo 2019; Jozanikohan 2017; Govindan et al. 2020
	Land disturbance (EN4)	Zanbak and Karahan 2005; Amirshenava and Osanloo 2019
	Water discharge (EN5)	Zanbak and Karahan 2005; Amirshenava and Osanloo 2018
Social (SC)	Job creation (SC1)	Zanbak and Karahan 2005
	Creating development (SC2)	Kretschmann and Amiri 2013
	Occupational health and safety systems (SC3)	Petersen and Bullock 2005; Amirshenava and Osanloo 2018; Luo et al. 2019; Amirshenava and Osanloo 2019
	The interests and rights of employees (SC4)	Petersen and Bullock 2005
	The rights of stakeholders (SC5)	Petersen and Bullock 2005

Table 7. The best and worst criteria and sub-criteria

Tabela 7. Najlepsze i najgorsze kryteria i podkryteria

	The best	The worst
Criteria	Economic	Environmental
Economic sub-criteria	Economic benefits	Use of energy
Environmental sub-criteria	Environmental management systems	Water discharge
Social sub-criteria	Creating development	Recreation and tourism

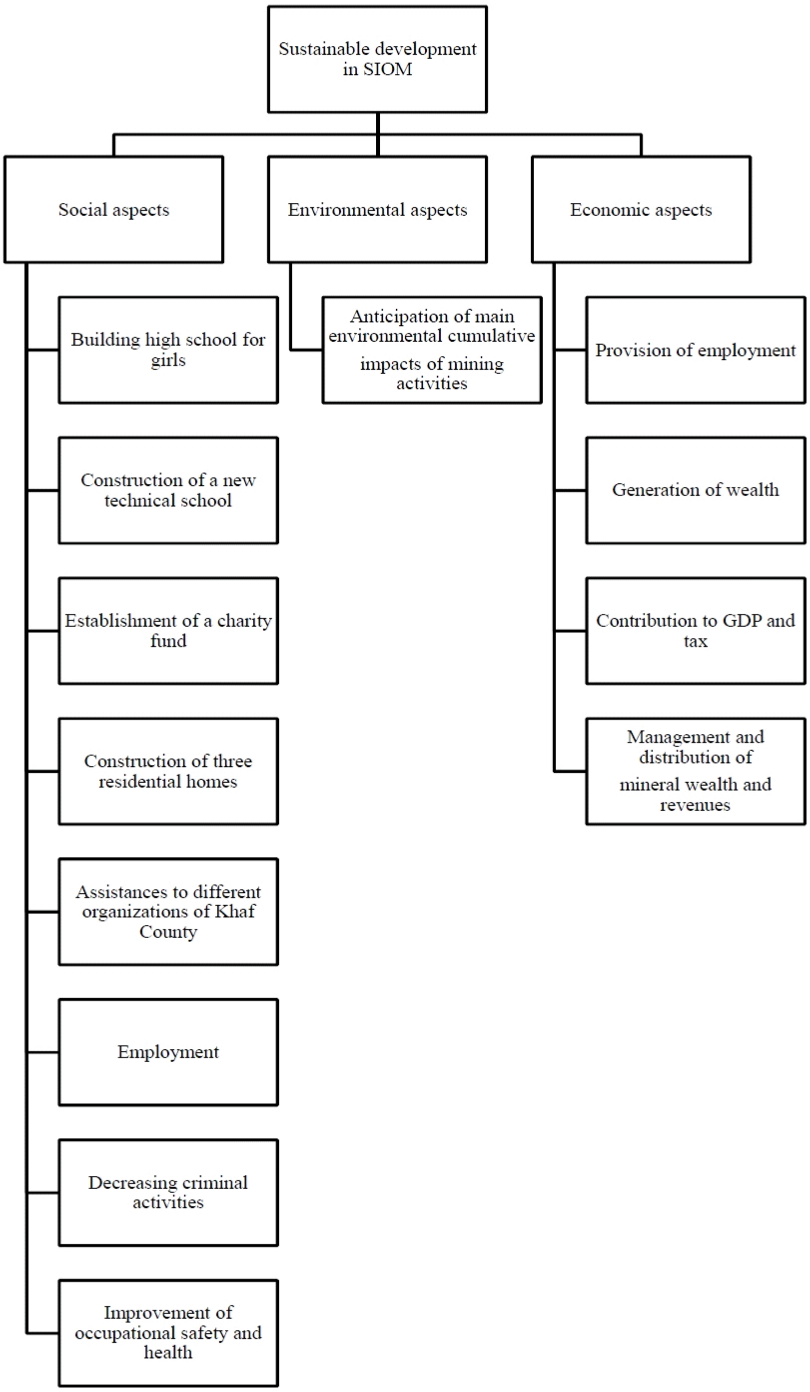

Fig. 5. The explanation of Criteria and sub-criteria in sustainable development of SIOM

Rys. 5. Wyjaśnienie kryteriów i podkryteriów w zrównoważonym rozwoju SIOM (*Sangan Iron Ore Mines*)

- **Step 3:** In this step, using Table 2, the best criteria (sub-criteria) are compared with the other criteria (sub-criteria) and the Best-to-Others vector is formed as follows:

The fuzzy Best-to-Others vector for economic criterion:

$$\tilde{A}_{B-CR}=\left[(1,1,1),\left(\frac{3}{2},2,\frac{5}{2}\right),\left(\frac{2}{3},1,\frac{3}{2}\right)\right]$$

The fuzzy Best-to-Others vector for economic benefits sub-criterion:

$$\tilde{A}_{B-EC}=\left[\left(\frac{5}{2},3,\frac{7}{2}\right),\left(\frac{2}{3},1,\frac{3}{2}\right),\left(\frac{3}{2},2,\frac{5}{2}\right),(1,1,1),\left(\frac{2}{3},1,\frac{3}{2}\right),\left(\frac{7}{2},4,\frac{9}{2}\right),\left(\frac{5}{2},3,\frac{7}{2}\right)\right]$$

The fuzzy Best-to-Others vector for environmental management systems sub-criterion:

$$\tilde{A}_{B-EN}=\left[(1,1,1),\left(\frac{3}{2},2,\frac{5}{2}\right),\left(\frac{3}{2},2,\frac{5}{2}\right),\left(\frac{2}{3},1,\frac{3}{2}\right),\left(\frac{5}{2},3,\frac{7}{2}\right)\right]$$

The fuzzy Best-to-Others vector for creating development sub-criterion:

$$\tilde{A}_{B-SC}=\left[\left(\frac{3}{2},2,\frac{5}{2}\right),(1,1,1),\left(\frac{3}{2},2,\frac{5}{2}\right),\left(\frac{2}{3},1,\frac{3}{2}\right),\left(\frac{2}{3},1,\frac{3}{2}\right),\left(\frac{5}{2},3,\frac{7}{2}\right)\right]$$

- **Step 4:** In this step, using Table 2, a paired-comparison is implemented between the other criteria (sub-criteria) and the worst-case (sub-criterion), and the Others-to-Worst vector is calculated for their criteria and sub-criteria, as follows:

The fuzzy Others-to-Worst vector for economic criterion:

$$\tilde{A}_{W-CR}=\left[\left(\frac{3}{2},2,\frac{5}{2}\right),(1,1,1),\left(\frac{2}{3},1,\frac{3}{2}\right)\right]$$

The fuzzy Others-to-Worst vector for economic benefits sub-criterion:

$$\tilde{A}_{W-EC}=\left[\left(\frac{2}{3},1,\frac{3}{2}\right),\left(\frac{5}{2},3,\frac{7}{2}\right),\left(\frac{3}{2},2,\frac{5}{2}\right),\left(\frac{7}{2},4,\frac{9}{2}\right),\left(\frac{5}{2},3,\frac{7}{2}\right),(1,1,1),\left(\frac{2}{3},1,\frac{3}{2}\right)\right]$$

The fuzzy Others-to-Worst vector for environmental management systems sub-criterion:

$$\tilde{A}_{W-EN}=\left[\left(\frac{5}{2},3,\frac{7}{2}\right),\left(\frac{3}{2},2,\frac{5}{2}\right),\left(\frac{2}{3},1,\frac{3}{2}\right),\left(\frac{2}{3},1,\frac{3}{2}\right),(1,1,1)\right]$$

The fuzzy Others-to-Worst vector for creating development sub-criterion:

$$\tilde{A}_{W-SC} = \left[\left(\frac{2}{3},1,\frac{3}{2}\right),\left(\frac{5}{2},3,\frac{7}{2}\right),\left(\frac{2}{3},1,\frac{3}{2}\right),\left(\frac{3}{2},2,\frac{5}{2}\right),\left(\frac{3}{2},2,\frac{5}{2}\right),(1,1,1)\right]$$

- **Step 5:** In this step, the weights of the criteria and sub-criteria are calculated using Eq. (3). As an example, calculating the weights of sub-criteria of the economic criteria is described here. By determining the best and worst criteria and by applying Eq. (4), we have:

$$Min\ \tilde{\mu}^*$$

$$St:$$

$$\left|\frac{(l_4^w, m_4^w, u_4^w)}{(l_1^w, m_1^w, u_1^w)} - (l_{41}, m_{41}, u_{41})\right| \le (o^*, o^*, o^*)$$

$$\left|\frac{(l_4^w, m_4^w, u_4^w)}{(l_2^w, m_2^w, u_2^w)} - (l_{42}, m_{42}, u_{42})\right| \le (o^*, o^*, o^*)$$

$$\left|\frac{(l_4^w, m_4^w, u_4^w)}{(l_3^w, m_3^w, u_3^w)} - (l_{43}, m_{43}, u_{43})\right| \le (o^*, o^*, o^*)$$

$$\left|\frac{(l_4^w, m_4^w, u_4^w)}{(l_4^w, m_4^w, u_4^w)} - (l_{44}, m_{44}, u_{44})\right| \le (o^*, o^*, o^*)$$

$$\left|\frac{(l_4^w, m_4^w, u_4^w)}{(l_5^w, m_5^w, u_5^w)} - (l_{45}, m_{45}, u_{45})\right| \le (o^*, o^*, o^*)$$

$$\left|\frac{(l_4^w, m_4^w, u_4^w)}{(l_6^w, m_6^w, u_6^w)} - (l_{46}, m_{46}, u_{46})\right| \le (o^*, o^*, o^*)$$

$$\left|\frac{(l_4^w, m_4^w, u_4^w)}{(l_7^w, m_7^w, u_7^w)} - (l_{47}, m_{47}, u_{47})\right| \le (o^*, o^*, o^*)$$

$$\left|\frac{(l_1^w, m_1^w, u_1^w)}{(l_6^w, m_6^w, u_6^w)} - (l_{16}, m_{16}, u_{16})\right| \le (o^*, o^*, o^*)$$

$$\left|\frac{(l_2^w, m_2^w, u_2^w)}{(l_6^w, m_6^w, u_6^w)} - (l_{26}, m_{26}, u_{26})\right| \leq (o^*, o^*, o^*)$$

$$\left|\frac{(l_3^w, m_3^w, u_3^w)}{(l_6^w, m_6^w, u_6^w)} - (l_{36}, m_{36}, u_{36})\right| \leq (o^*, o^*, o^*)$$

$$\left|\frac{(l_4^w, m_4^w, u_4^w)}{(l_6^w, m_6^w, u_6^w)} - (l_{46}, m_{46}, u_{46})\right| \leq (o^*, o^*, o^*)$$

$$\left|\frac{(l_5^w, m_5^w, u_5^w)}{(l_6^w, m_6^w, u_6^w)} - (l_{56}, m_{56}, u_{56})\right| \leq (o^*, o^*, o^*)$$

$$\left|\frac{(l_6^w, m_6^w, u_6^w)}{(l_6^w, m_6^w, u_6^w)} - (l_{66}, m_{66}, u_{66})\right| \leq (o^*, o^*, o^*)$$

$$\left|\frac{(l_7^w, m_7^w, u_7^w)}{(l_6^w, m_6^w, u_6^w)} - (l_{76}, m_{76}, u_{76})\right| \leq (o^*, o^*, o^*)$$

$$\sum_j R(\tilde{w}_j) = 1$$

$$l_j^w \leq m_j^w \leq u_j^w$$

$$l_j^w \geq 0$$

By replacing the values of the Best-to-Others vector and the Others-to-Best vector into the above model, we have:

$$Min\ o^*$$

$$St:$$

$$\left|\frac{l_4}{u_1} - 2.5\right| \leq o; \qquad \left|\frac{m_4}{m_1} - 3\right| \leq o; \qquad \left|\frac{u_4}{l_1} - 3.5\right| \leq o$$

$$\left|\frac{l_4}{u_2}-0.667\right|\le o;\quad \left|\frac{m_4}{m_2}-1\right|\le o;\quad \left|\frac{u_4}{l_2}-1.5\right|\le o$$

$$\left|\frac{l_4}{u_3}-1.5\right|\le o;\quad \left|\frac{m_4}{m_3}-2\right|\le o;\quad \left|\frac{u_4}{l_3}-2.5\right|\le o$$

$$\left|\frac{l_4}{u_5}-0.667\right|\le o;\quad \left|\frac{m_4}{m_5}-1\right|\le o;\quad \left|\frac{u_4}{l_5}-1.5\right|\le o$$

$$\left|\frac{l_4}{u_6}-3.5\right|\le o;\quad \left|\frac{m_4}{m_6}-4\right|\le o;\quad \left|\frac{u_4}{l_6}-4.5\right|\le o$$

$$\left|\frac{l_4}{u_7}-2.5\right|\le o;\quad \left|\frac{m_4}{m_7}-3\right|\le o;\quad \left|\frac{u_4}{l_7}-3.5\right|\le o$$

$$\left|\frac{l_1}{u_6}-0.667\right|\le o;\quad \left|\frac{m_1}{m_6}-1\right|\le o;\quad \left|\frac{u_1}{l_6}-1.5\right|\le o$$

$$\left|\frac{l_2}{u_6}-2.5\right|\le o;\quad \left|\frac{m_2}{m_6}-3\right|\le o;\quad \left|\frac{u_2}{l_6}-3.5\right|\le o$$

$$\left|\frac{l_3}{u_6}-1.5\right|\le o;\quad \left|\frac{m_3}{m_6}-2\right|\le o;\quad \left|\frac{u_3}{l_6}-2.5\right|\le o$$

$$\left|\frac{l_5}{u_6}-2.5\right|\le o;\quad \left|\frac{m_5}{m_6}-3\right|\le o;\quad \left|\frac{u_5}{l_6}-3.5\right|\le o$$

$$\left|\frac{l_5}{u_6}-2.5\right|\le o;\quad \left|\frac{m_5}{m_6}-3\right|\le o;\quad \left|\frac{u_5}{l_6}-3.5\right|\le o$$

$$\left(\frac{l_1+4\cdot m_1+u_1}{6}\right)+\left(\frac{l_2+4\cdot m_2+u_2}{6}\right)+\left(\frac{l_3+4\cdot m_3+u_3}{6}\right)+\left(\frac{l_4+4\cdot m_4+u_4}{6}\right)+$$
$$+\left(\frac{l_5+4\cdot m_5+u_5}{6}\right)+\left(\frac{l_6+4\cdot m_6+u_6}{6}\right)+\left(\frac{l_7+4\cdot m_7+u_7}{6}\right)=1$$

$$l_1\le m_1\le u_1;\quad l_2\le m_2\le u_2;\quad l_3\le m_3\le u_3;\quad l_4\le m_4\le u_4;$$
$$l_5\le m_5\le u_5;\quad l_6\le m_6\le u_6;\quad l_7\le m_7\le u_7$$

$l_1,l_2,l_3,l_4,l_5,l_6,l_7>0$ and $o\ge 0$

By extending expressions that include absolute terms, the mathematical model will be as follows:

*Min o**

St:

$$l_4 - 2.5 \cdot u_1 \le o \cdot u_1; \qquad l_4 - 2.5 \cdot u_1 \ge -o \cdot u_1$$
$$m_4 - 3 \cdot m_1 \le o \cdot m_1; \qquad m_4 - 3 \cdot m_1 \ge -o \cdot m_1$$
$$u_4 - 3.5 \cdot l_1 \le o \cdot l_1; \qquad u_4 - 3.5 \cdot l_1 \ge -o \cdot l_1$$

$$l_4 - 0.667 \cdot u_2 \le o \cdot u_2; \qquad l_4 - 0.667 \cdot u_2 \ge -o \cdot u_2$$
$$m_4 - m_2 \le o \cdot m_2; \qquad m_4 - m_2 \ge -o \cdot m_2$$
$$u_4 - 1.5 \cdot l_2 \le o \cdot l_2; \qquad u_4 - 1.5 \cdot l_2 \ge -o \cdot l_2$$

$$l_4 - 1.5 \cdot u_3 \le o \cdot u_3; \qquad l_4 - 1.5 \cdot u_3 \ge -o \cdot u_3$$
$$m_4 - 2 \cdot m_3 \le o \cdot m_3; \qquad m_4 - 2 \cdot m_3 \ge -o \cdot m_3$$
$$u_4 - 2.5 \cdot l_3 \le o \cdot l_3; \qquad u_4 - 2.5 \cdot l_3 \ge -o \cdot l_3$$

$$l_4 - 0.667 \cdot u_5 \le o \cdot u_5; \qquad l_4 - 0.667 \cdot u_5 \ge -o \cdot u_5$$
$$m_4 - m_5 \le o \cdot m_5; \qquad m_4 - m_5 \ge -o \cdot m_5$$
$$u_4 - 1.5 \cdot l_5 \le o \cdot l_5; \qquad u_4 - 1.5 \cdot l_5 \ge -o \cdot l_5$$

$$l_4 - 3.5 \cdot u_6 \le o \cdot u_6; \qquad l_4 - 3.5 \cdot u_6 \ge -o \cdot u_6$$
$$m_4 - 4 \cdot m_6 \le o \cdot m_6; \qquad m_4 - 4 \cdot m_6 \ge -o \cdot m_6$$
$$u_4 - 4.5 \cdot l_6 \le o \cdot l_6; \qquad u_4 - 4.5 \cdot l_6 \ge -o \cdot l_6$$

$$l_4 - 2.5 \cdot u_7 \le o \cdot u_7; \qquad l_4 - 2.5 \cdot u_7 \ge -o \cdot u_7$$
$$m_4 - 3 \cdot m_7 \le o \cdot m_7; \qquad m_4 - 3 \cdot m_7 \ge -o \cdot m_7$$
$$u_4 - 3.5 \cdot l_7 \le o \cdot l_7; \qquad u_4 - 3.5 \cdot l_7 \ge -o \cdot l_7$$

$$l_1 - 0.667 \cdot u_6 \le o \cdot u_6; \qquad l_1 - 0.667 \cdot u_6 \ge -o \cdot u_6$$
$$m_1 - m_6 \le o \cdot m_6; \qquad m_1 - m_6 \ge -o \cdot m_6$$
$$u_1 - 1.5 \cdot l_6 \le o \cdot l_6; \qquad u_1 - 1.5 \cdot l_6 \ge -o \cdot l_6$$

$$l_2 - 2.5 \cdot u_6 \le o \cdot u_6; \qquad l_2 - 2.5 \cdot u_6 \ge -o \cdot u_6$$
$$m_2 - 3 \cdot m_6 \le o \cdot m_6; \qquad m_2 - 3 \cdot m_6 \ge -o \cdot m_6$$
$$u_2 - 3.5 \cdot l_6 \le o \cdot l_6; \qquad u_2 - 3.5 \cdot l_6 \ge -o \cdot l_6$$

$$l_3 - 1.5 \cdot u_6 \le o \cdot u_6; \qquad l_3 - 1.5 \cdot u_6 \ge -o \cdot u_6$$
$$m_3 - 2 \cdot m_6 \le o \cdot m_6; \qquad m_3 - 2 \cdot m_6 \ge -o \cdot m_6$$
$$u_3 - 2.5 \cdot l_6 \le o \cdot l_6; \qquad u_3 - 2.5 \cdot l_6 \ge -o \cdot l_6$$

$$l_5 - 2.5 \cdot u_6 \le o \cdot u_6; \qquad l_5 - 2.5 \cdot u_6 \ge -o \cdot u_6$$
$$m_5 - 3 \cdot m_6 \le o \cdot m_6; \qquad m_5 - 3 \cdot m_6 \ge -o \cdot m_6$$
$$u_5 - 3.5 \cdot l_6 \le o \cdot l_6; \qquad u_5 - 3.5 \cdot l_6 \ge -o \cdot l_6$$

$$l_7 - 0.667 \cdot u_6 \le o \cdot u_6; \qquad l_7 - 0.667 \cdot u_6 \ge -o \cdot u_6$$
$$m_7 - m_6 \le o \cdot m_6; \qquad m_7 - m_6 \ge -o \cdot m_6$$
$$u_7 - 1.5 \cdot l_6 \le o \cdot l_6; \qquad u_7 - 1.5 \cdot l_6 \ge -o \cdot l_6$$

$$\left(\frac{l_1 + 4 \cdot m_1 + u_1}{6}\right) + \left(\frac{l_2 + 4 \cdot m_2 + u_2}{6}\right) + \left(\frac{l_3 + 4 \cdot m_3 + u_3}{6}\right) + \left(\frac{l_4 + 4 \cdot m_4 + u_4}{6}\right) +$$
$$+ \left(\frac{l_5 + 4 \cdot m_5 + u_5}{6}\right) + \left(\frac{l_6 + 4 \cdot m_6 + u_6}{6}\right) + \left(\frac{l_7 + 4 \cdot m_7 + u_7}{6}\right) = 1$$

$$l_1 \le m_1 \le u_1; \qquad l_2 \le m_2 \le u_2; \qquad l_3 \le m_3 \le u_3; \qquad l_4 \le m_4 \le u_4;$$
$$l_5 \le m_5 \le u_5; \qquad l_6 \le m_6 \le u_6; \qquad l_7 \le m_7 \le u_7$$

$$l_1, l_2, l_3, l_4, l_5, l_6, l_7 > 0 \quad \text{and} \quad o \ge 0$$

Having implemented the mathematical model in GAMS software using COUENNE solver, the optimal local weight criteria are obtained as triangular fuzzy numbers. GAMS is considered as a prominent tool provider that is used in the optimization industry whose departments and offices are situated in the US and Germany. In fact, GAMS has many customers in various countries (even higher than 120 countries) and, thereby, it is highly employed by multinational business ventures, universities and colleges, research departments, states in a variety of domains, such as industries of energy and chemical materials for the purpose of economic modelling, agricultural plans, or production systems. It is notable that GAMS was initiated as a project in the World Bank in the 1970s. In fact, they were an economic modeling group who embarked on working with it and is regarded as the first software that merges the traditional idea of computer programming and language of mathematical algebra together with the aim of providing an efficient description and resolution of optimization problems. Gradually, in 1987, this software came into play as a commercial product and, accordingly, the GAMS Development Corporation was established in Washington, D.C. Today, algebraic modeling is referred to as one of the best productive methods for the implementation of optimization models and problems (https://www.gams.com/about-the-company/).

The fuzzy local weights obtained for the criteria and sub-criteria using the detailed method are shown in Tables 8 and 9, respectively. For the ease of making a comparison between the weights of the criteria and the sub-criteria, the local weights of the criteria and sub-criteria are given in Figure 6 and 7, respectively. The obtained results show that the economic

Table 8. The fuzzy local weight of criteria

Tabela 8. Rozmyta lokalna waga kryteriów

Criteria	*l*	*m*	*u*
Economic (EC)	0.376	0.413	0.510
Environmental (EN)	0.226	0.243	0.307
Social (SC)	0.290	0.317	0.399

Table 9. The fuzzy local weight of sub-criteria

Tabela 9. Rozmyta lokalna waga podkryteriów

Sub-criteria	*l*	*m*	*u*
Exploration capacity (EC1)	0.066	0.079	0.093
Technological and financial capacity (EC2)	0.169	0.204	0.228
Production facility and capability (EC3)	0.101	0.129	0.156
Economic benefits (EC4)	0.220	0.245	0.252
Rate of return (EC5)	0.169	0.204	0.228
Use of energy (EC6)	0.060	0.065	0.069
Applying research and development (EC7)	0.066	0.079	0.093
Environmental management systems (EN1)	0.255	0.307	0.358
Waste management (EN2)	0.138	0.172	0.205
Air emissions (EN3)	0.138	0.172	0.205
Land disturbance (EN4)	0.192	0.224	0.257
Water discharge (EN5)	0.105	0.125	0.144
Job creation (SC1)	0.136	0.154	0.173
Creating development (SC2)	0.224	0.252	0.281
Occupational health and safety systems (SC3)	0.136	0.154	0.173
The interests and rights of employees (SC4)	0.155	0.179	0.204
The rights of stakeholders (SC5)	0.155	0.179	0.204
Recreation and tourism (SC6)	0.075	0.082	0.088

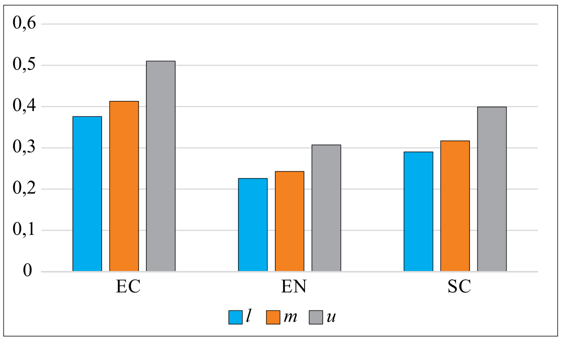

Fig. 6. Comparison of criteria local weights

Rys. 6. Porównanie lokalnych wag kryteriów

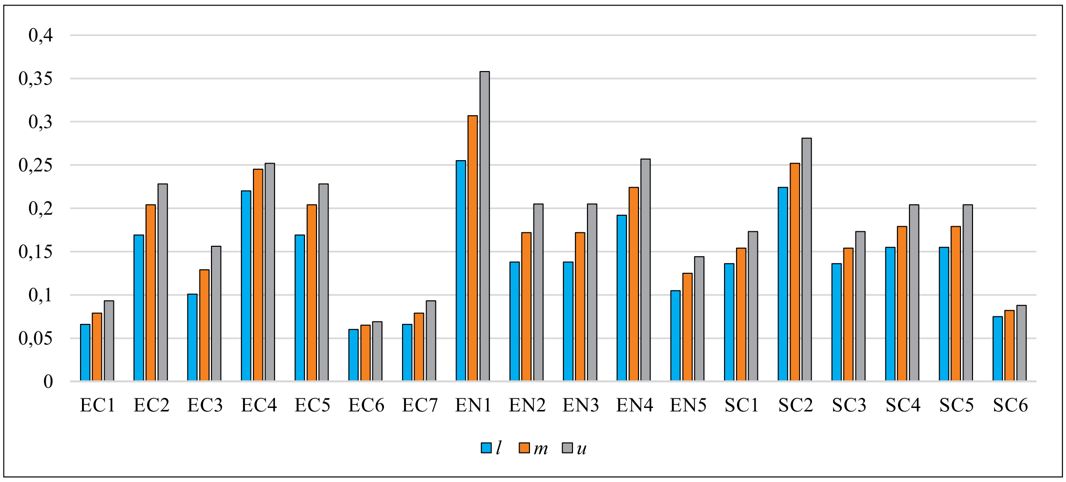

Fig. 7. Comparison of sub-criteria local weights

Rys. 7. Porównanie lokalnych wag podkryteriów

and the environmental criteria are the best and worst criterion, respectively. In the same way, EC4 and EC6 were also identified as the best and worst economic sub-criteria, respectively. Moreover, the results demonstrate that EN1 and EN5 are the best and worst environmental sub-criteria and SC2 and SC6 are the best and worst social sub-criteria, respectively. These results are fully consistent with the classification made by experts, which indicates the precise performance of the proposed model.

To obtain global weight of sub-criteria, the local weight criteria should be multiplied by the local weight sub-criteria, the results of which are presented in Table 10 and Figure 8.

The results presented in Table 10 and Figure 7 show that among all economic, environmental, and social sub-criteria, and EC4 sub-criterion are of higher importance than other sub-criteria and, thereby, emphasis on this sub-criterion can influence the performance of

Table 10. The fuzzy global weight of sub-criteria

Tabela 10. Rozmyta globalna waga podkryteriów

Sub-criteria	*l*	*m*	*u*
Exploration capacity (EC1)	0.0248	0.0326	0.0474
Technological and financial capacity (EC2)	0.0635	0.0843	0.1163
Production facility and capability (EC3)	0.0380	0.0533	0.0796
Economic benefits (EC4)	0.0827	0.1012	0.1285
Rate of return (EC5)	0.0635	0.0843	0.1163
Use of energy (EC6)	0.0226	0.0268	0.0352
Applying research and development (EC7)	0.0248	0.0326	0.0474
Environmental management systems (EN1)	0.0576	0.0746	0.1099
Waste management (EN2)	0.0312	0.0418	0.0629
Air emissions (EN3)	0.0312	0.0418	0.0629
Land disturbance (EN4)	0.0434	0.0544	0.0789
Water discharge (EN5)	0.0237	0.0304	0.0442
Job creation (SC1)	0.0394	0.0488	0.0690
Creating development (SC2)	0.0650	0.0799	0.1121
Occupational health and safety systems (SC3)	0.0394	0.0488	0.0690
The interests and rights of employees (SC4)	0.0450	0.0567	0.0814
The rights of stakeholders (SC5)	0.0450	0.0567	0.0814
Recreation and tourism (SC6)	0.0218	0.0260	0.0351

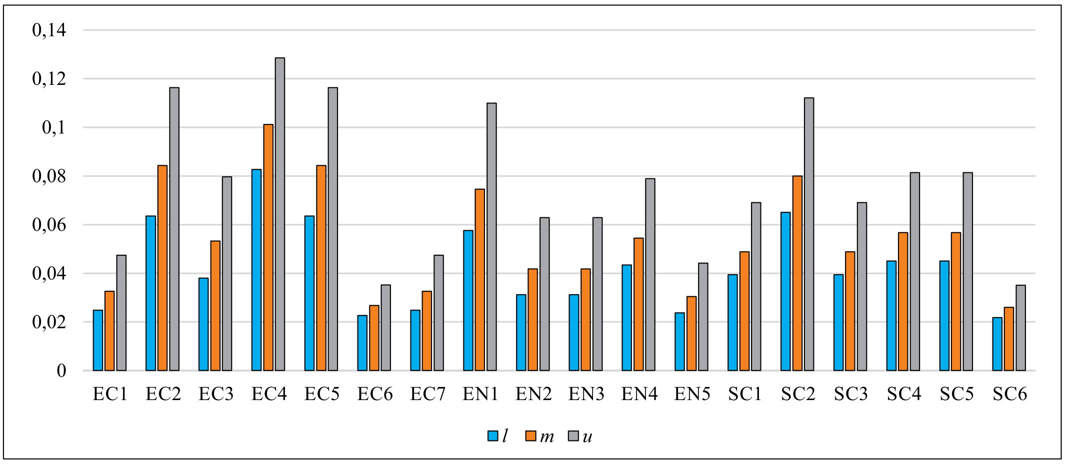

Fig. 8. Comparison of sub-criteria global weights

Rys. 8. Porównanie globalnych wag podkryteriów the studied system more than ever. On the other hand, sub-criteria such as EC6 and SC6 are less important than other sub-criteria and, thereby, the focus on these sub-criteria will not significantly change the performance of the system.

- **Step 6:** As mentioned earlier, the consistency ratio is an important indicator for measuring the consistency of pairwise comparisons. Its closeness to zero indicates its higher consistency. In Table 11, the consistency ratio is computed for pairwise comparisons that indicate high consistency in paired comparisons. It is because the consistency ratio for each pairwise comparison is very close to zero. Therefore, the weights obtained for the criteria and sub-criteria are confirmed.

Table 11. The consistency ratio

Tabela 11. Współczynnik spójności

	o^*	The consistency index	The consistency ratio
Criteria	0.303	5.29	0.057
Economic sub-criteria	0.299	8.04	0.037
Environmental sub-criteria	0.391	6.69	0.058
Social sub-criteria	0.345	6.69	0.052

- **Step 7:** In this step, the mine will be evaluated. For this purpose, a performance evaluation questionnaire was provided to 12 experts and they were asked to rate the mine under study per each sub-criterion using Table 4. The average value of opinions is given in Table 12.

Now, using the results of Tables 9 and 11 and applying Eq. (8), the final fuzzy score is calculated. Then, using Eq. (9), the final score was gone under defuzzification process.

$$Fuzzy\ final\ score = \sum_{j=1}^{n} (l_j^w, m_j^w, u_j^w) \otimes (l_j^X, m_j^X, u_j^X) = (0.393, 0.597, 0.976)$$

$$Defuzzy\ final\ score = \sum_{j=1}^{n} \frac{(l_j^w \cdot l_j^X) + 4 \cdot (m_j^w \cdot m_j^X) + (u_j^w \cdot u_j^X)}{6} = 0.626$$

The performance of the SIOM was evaluated from sustainable development perspective, and the mine scored 0.626 out of 1 indicating its acceptable performance. As it is shown in Table 12, the mine performs well in terms of economic benefits, rate of return, exploration capacity, and stockholders' rights, but in environmental management systems, water discharge, recreation and tourism fields it does not play well. Therefore, it is suggested to make strategies in line with improving unacceptable criteria.

Table 12. Evaluating SIOM per each sub-criterion according to average of experts' opinion

Tabela 12. Ocena SIOM (*Sangan Iron Ore Mines*) według każdego podkryterium na podstawie średniej opinii ekspertów

Sub-criteria	*l*	*m*	*u*
Exploration capacity (EC1)	0.650	0.750	0.850
Technological and financial capacity (EC2)	0.583	0.683	0.783
Production facility and capability (EC3)	0.583	0.683	0.783
Economic benefits (EC4)	0.683	0.783	0.883
Rate of return (EC5)	0.750	0.850	0.950
Use of energy (EC6)	0.500	0.600	0.700
Applying research and development (EC7)	0.317	0.417	0.517
Environmental management systems (EN1)	0.267	0.350	0.450
Waste management (EN2)	0.317	0.417	0.517
Air emissions (EN3)	0.267	0.367	0.467
Land disturbance (EN4)	0.317	0.417	0.517
Water discharge (EN5)	0.267	0.350	0.450
Job creation (SC1)	0.600	0.700	0.800
Creating development (SC2)	0.517	0.617	0.717
Occupational health and safety systems (SC3)	0.600	0.700	0.800
The interests and rights of employees (SC4)	0.583	0.683	0.783
The rights of stakeholders (SC5)	0.667	0.767	0.867
Recreation and tourism (SC6)	0.167	0.233	0.333

Conclusion

The performance evaluation in industries has a remarkable impact on improving their performance. The evaluation of mines and mining industries, as non-sustainable industries, have a significant effect on economic, social and environmental improvement. Therefore, in this paper, SIOM is evaluated from sustainable development viewpoint using fuzzy BWM. In the proposed approach, the evaluation sub-criteria were extracted from the literature and knowledge of experts from three economic, environmental and social perspectives. The sub-criteria then were weighted using the fuzzy BWM method and the mine was evaluated per each sub-criterion by 12 experts. Afterwards, the sustainability score obtained from SIOM performance evaluation was calculated.

As for the future research, it is recommended to employ the proposed approach to evaluate other mines and mining industries. Also, the intra-criterion interdependence could be measured using methods such as DEMATEL and applied to the weight of the metrics. This incorporate inter-dependency in the performance evaluation process that might lead to meaningful changes.

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AN APPROACH BASED ON FUZZY BEST-WORST METHOD FOR SUSTAINABLE EVALUATION OF MINING INDUSTRIES

Keywords

sustainable development, mining industry, best-worst method, fuzzy theory

Abstract

The mines play an important role in the economic growth of countries since they are suppliers to many industries. In addition to the economic growth, the mines positively affect the social development factors such as the employment creation, the development of rural areas, building new roads, and etc. But sometimes it may lead to the negative environmental, and social impacts. Therefore, the mining activities should be carefully monitored for the concept of sustainable development. In this paper, a fuzzy Best-Worst Method based approach is developed for the evaluation of an iron mine. The case study, Sangan iron ore mine is one of the biggest mines, located in a rural area in the north eastern of Iran. Three factors including the economic, environmental, and social parameters were considered as main sustainable development criteria. The sub-criteria for each mentioned factor were then extracted from the literature as well as knowledge expert's opinions. In the proposed approach, each sub-criterion was carefully weighted using the fuzzy Best-Worst method and scored by 12 experts. Afterwards, the sustainability score was defined as the summation of final fuzzy scores which was gone under a defuzzification process. The performance evaluation was calculated using this sustainability score resulted to a score of 0.626 out of 1, indicating its acceptable performance. The results showed that the mine performs well in terms of the economic benefits, rate of return, exploration capacity, and stockholders' rights, but in the environmental management systems, water discharge, recreation and tourism aspects, it does not play well. The results of the implementation of the proposed approach showed the efficiency and effectiveness of the proposed approach that is confirmed by experts.

PODEJŚCIE OPARTE NA METODZIE ROZMYTEJ BEST-WORST DLA ZRÓWNOWAŻONEJ OCENY PRZEMYSŁU WYDOBYWCZEGO

Słowa kluczowe

zrównoważony rozwój, górnictwo, BWM, teoria zbiorów rozmytych

Streszczenie

Kopalnie odgrywają ważną rolę we wzroście gospodarczym krajów, ponieważ są dostawcami dla wielu branż. Oprócz wzrostu gospodarczego kopalnie pozytywnie wpływają na czynniki rozwoju społecznego, takie jak tworzenie miejsc pracy, rozwój obszarów wiejskich, budowa nowych dróg itp. Ale czasami może to mieć negatywny wpływ na środowisko przyrodnicze i społeczeństwo. Dlatego działania górnicze powinny być uważnie monitorowane pod kątem koncepcji zrównoważonego rozwoju. W tym artykule zastosowano rozmyte podejście BWM (*Best-Worst Method*) do oceny kopalni żelaza. Studium przypadku, kopalnia rudy żelaza Sangan, jest jedną z największych kopalń zlokalizowanych na obszarach wiejskich w północno-wschodnim Iranie. Trzy główne czynniki, w tym parametry ekonomiczne, środowiskowe i społeczne, zostały uznane za główne kryteria zrównoważonego rozwoju. Podkryteria dla każdego z wymienionych czynników zostały następnie opracowane na podstawie literatury, a także podane przez ekspertów. W proponowanym podejściu każde podkryterium zostało starannie wyważone przy użyciu metody rozmytej BWM i ocenione przez 12 ekspertów. Następnie wynik zrównoważonego rozwoju został zdefiniowany jako suma końcowych wyników rozmytych, które przeszły proces rozmywania (fuzyfikacji). Ocena efektywności została obliczona przy zastosowaniu wyniku zrównoważonego rozwoju, co dało wynik 0,626 na 1, wskazując jego akceptowalną przydatność. Wyniki pokazały, że kopalnia działa dobrze pod względem korzyści ekonomicznych, stopy zwrotu kapitału, zdolności poszukiwawczej i praw akcjonariuszy, natomiast nie w systemach zarządzania środowiskiem przyrodniczym, zrzutach wody, rekreacji i turystyce. Wyniki wdrożenia proponowanego podejścia wykazały efektywność i skuteczność proponowanego podejścia, co potwierdzają eksperci.