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An integrated approach for performance evaluation of mining industry: a case study of Iranian Steel Complex

Introduction

The emergence of the term sustainable development and the consequent concepts has come into being since the beginning of 1970s. In 1980, the International Union for Conservation of Nature and Natural Resources first provided a definition for sustainable development (Asr et al. 2019). This term is used by that organization when the nature is not threatened but is supported (Asr et al. 2019). Later on in 1992, the World Commission on Environment and Development convened a meeting in Rio de Janeiro, Brazil and some factors like local, national, and global criteria were discussed for the purpose of practicing a higher degree of sustainability on Earth. Besides environmental factors, socio-economic factors were also taken into consideration in defining the term sustainable development (Temple 1992).

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Since there is a wide range of applications for sustainable development, it is relatively difficult to present an inclusive definition for sustainability that includes all the disciplines (Nuong et al. 2011). Based on Brundtland Commission, sustainable development is defined as a process which can overcome the current needs of an organization while giving credit to the capability to meet the future needs (Asr et al. 2019). Therefore, sustainability is defined as a developmental plan considers both current and future needs of generations' lives (Cerin 2006; Dernbach 1998). Considering these points, sustainable development carries some traces of social, economic, environmental and cultural needs of humans as well as other human needs. In this regard, comprehensiveness can lead to higher rates of sustainability (Rajaram et al. 2005; Botin 2009).

The application of sustainable development in the field of mining was initiated at the United Nations Conference, Rio de Janeiro, Brazil in 1992 (Rahmanpour and Osanloo 2017). From that time onwards, different definitions have been proposed for sustainable development in mining and its practice in the domain of mining. In this regard, Allan (Allan 1995) is the one who brought sustainability to the literature of mining industry in such a way that the usage of minerals was not larger than the capacity of new resources. On the other hand, some scholars believe that the mere introduction of the concept of sustainability in the mining industry cannot be considered as a holistic sustainable affair sue to the little lifespan of mines and the huge dependence of human beings on non-renewable sources (Crowson 1998; Rajaram et al. 2005). However, other researchers claim that mining is regarded as a sustainable task in the long run (Basu and Kumar 2004) and this sustainability can create different chances for the economic progress of the related organizations and communities (McLellan et al. 2009). Through a more inclusive perspective, one may regards the mining industry as an entity with long-lasting value chains that are initiated with exploring mineral sources and then go on by such affairs as the design, construction, and exploitation affairs in the next years and decades (Pimentel et al. 2016). During different stages of developing the mining industry, there is the probability of the emergence of unwanted social and environmental factors, which necessitate the arrangement of a trade-off between these negative impacts and long-term economic profits (Lala et al. 2016). A large amount of capital costs may be imposed on the operating mines wherein both efficiency and budget have a pivotal role. Some researchers argue that the rise in capital and operational costs may exert a considerable effect on the mines' productivity (Pezeshkan and Navid 2020). Therefore, important decisions should be made based on the results of economic analysis while considering environmental and social viewpoints in order to fulfill sustainable goals.

The approach proposed in this paper is a development of approach presented by Pezeshkan and Navid (Pezeshkan and Navid 2020). They developed an approach based on fuzzy BWM for mining industries evaluation considering sustainable criteria. Hence, in this paper a hybrid approach based onmulti-criteria decision making (MCDM) methods and fuzzy theory has been used to evaluate the performance of a steel complex considering triple line bottom (i.e. economic, environmental, and social). In the proposed approach, the weights of the criteria are computed by fuzzy BWM, and FIS is applied to compute the final score of steel complex. Based on expert opinion, it can be assumed that the relationship between the criteria of each aspect follows a linear function while computing the steel complex' score for each aspect because the criteria of each aspect are originally from the same family and have similar features. Therefore, MCDM methods can be used to calculate the weights of the criteria and, here, fuzzy BWM has also been used because of its high accuracy and the use of fewer pairwise comparisons. However, the final score of steel complex is not calculated from these aspect based on a linear function and nonlinear functions should be used for this purpose since economic, environmental, and social aspects are strongly influenced by each other. In such conditions, it is highly useful to use rule-based methods since these methods provide the possibility to define proper rules (functions) in different situations. The expert knowledge and the real data of the mentioned complex were used to validate the purposed method. As mentioned, the advantages of the presented approach are that the decrease of pairwise comparisons, increase of consistency, and the evaluation under uncertainty. One of the practical advantages of this approach is that it is not only limited to the studied case study but it can be implemented in the various scientific fields, such as supplier selection, healthcare industry evaluation, etc.

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 steel complex. Finally, conclusion explains in Section 5.

1. Literature review

These days, industries should collaborate with each other to approach sustainable development in different countries (Dubiński 2013). When it is followed by sustainability, the current types of mining are replaced by the modern types of mining (Hartman and Mutmansky 2002). In addition, some technical concepts, including Responsible Mining and Green Mining have been employed as the main elements of sustainability in different mines. Green mining refers to the minimization of the destructive effects imposed on the mines by the environment (Rahmanpour and Osanloo 2017) and responsible mining attempts to control the detrimental effects, especially the economic, environmental, and social ones that may result from mining activity (Jarvie-Eggart ed. 2015). For the initiation of sustainable mining, the evaluation of the effect of mining tasks on sustainability indexes and the subsequent prioritization of vulnerable sections are required (Fonseca et al. 2013; Marnika et al. 2015). Considering the significance of this issue, a lot of research has been carried out in this domain where the employment of semi-quantitative approaches for the evaluation of mining affairs on the indices of sustainable development has led to fruitful results, particularly in terms of social and environmental factors. The two-dimensional evaluation matrix is a frequently-used method in this domain due to its simple and useful features (Ghaedrahmati and Doulati Ardejani 2012). Leopold et al. (Leopold et al. 1971) first proposed the employment of the two-dimensional matrix for the evaluation of environmental threats where they assigned value to the quantity and quality of the effects that each activity had on the environmental elements. In the same vein, Schlickmann et al. (Schlickmann et al. 2018) made use of this method to evaluate the environmental effects in a coal mine. Then, Pastakia and Jensen (Pastakia and Jensen 1998) assessed the environmental effects in sand mining by using Rapid Impact Assessment Matrix. It is noteworthy that this method is used for the assessment of environmental factors regardless of the active project affairs. In this regard, Folchi (Folchi 2003) has developed a method to evaluate environmental effects on the basis of the assessment of mining activities and this method has become the most frequently used on in this domain of enquiry. In fact, the important mining affairs and environmental factors are assessed in this method. Moreover, Kauppinen and Khajehzadeh (Kauppinen et al. 2015) utilized data envelopment analysis method to assess sustainable development in the mining exploration stage.

One of the most commonly used methods in specifying and weighting the sustainability criteria has been MCDM methods. Anand et al. (Anand et al. 2017) proposed an approach based on MCDM methods for the assessment of sustainability indices at smart cities in India. Smart cities are the sustainable and efficient cities that provide high quality of life by making optimal use of their resources. In that research, the importance of different criteria for sustainability in a smart city was determined using fuzzy analytical hierarchy process (AHP) method. Ahmadi et al. (Ahmadi et al. 2017) believe that all three economic, environmental, and social aspects should be taken into account to have a sustainable organization. In practice, however, the social aspect has received less attention in developing countries. Therefore, they proposed a framework for examining the social sustainability of supply chains in manufacturing companies to address this issue. In this framework, the criteria were weighted and ranked using BWM. A hybrid approach using MCDM methods and sustainable balanced scorecard model was proposed by Lu et al. (Lu et al. 2018) for performance evaluation at international airports. They first extracted the evaluation criteria from the related literature and then calculated the interdependencies between the criteria using DEMATEL method. In the next step, they determined the weights of the criteria using the analytical network process. In the end, they ranked the alternatives through VIKOR technique. In this regard, Raj and Srivastava (Raj and Srivastava 2018) developed an approach based on fuzzy BWM for the sustainable performance evaluation of an aircraft manufacturer in India. Mavi and Standing (Mavi and Standing 2018) also developed an approach based on MCDM methods to identify and rank critical success factors of sustainable project management in construction under uncertainty conditions. To this end, they first extracted critical success factors from the literature and used the analytical network process method to weight these factors. In addition, they used DEMATEL method to calculate the interdependencies between the criteria. It is noteworthy that the fuzzy theory has been used to consider the uncertainty in the problem. Malek and Desai (Malek and Desai 2019) used BWM and presented an approach to prioritize sustainable production barriers in manufacturing organizations in India. They extracted 39 production barriers from the literature by using expert opinion, placed them in six classes, and weighted them using BWM. Their research findings introduce economic and managerial problems as the most important barriers. A sustainable approach was proposed by Govindan et al. (Govindan et al. 2019) using an integration of BWM and COPRAS method for partner selection in the reverse supply chain where all three aspects of sustainability, namely economic, environmental, and social ones were considered. An integrated performance evaluation approach based on MCDM methods was presented by Santos et al. (Santos et al. 2019) for supplier evaluation in the green supply chain. They used Shannon entropy method to weight the criteria and used TOPSIS technique to rank suppliers. Finally, they used the data and knowledge of experts in a Latin American furniture production chain to assess the efficiency of their proposed approach. Kannan et al. (Kannan et al. 2020) developed a novel hybrid approach for sustainable supplier evaluation. Their approach made use of the integrated fuzzy BWM and interval VIKOR method to evaluate suppliers. For this purpose, supplier evaluation criteria are first extracted from three of economic, social, and circular perspectives, and then these criteria are weighted using fuzzy BWM. Finally, the VIKOR interval method is used to rank the criteria. They benefited from the knowledge of experts of a cable and wire manufacturing company in Iran to evaluate the efficiency and effectiveness of their proposed approach.

Research findings indicate that MCDM is a proper method for ranking the criteria and assessing the mining industry. Accordingly, Sitorus et al. (Sitorus et al. 2018) investigated the dominant trend and usage of this method in the mining industry and presented an inclusive outline in this area. At the end, they argued that MCDM methods are among the most frequently used and effective methods in the area of expertise. Several researches have clearly showed the efficiency of MCDM technique with a systematic approach that can greatly help decision makers in different disciplines of engineering industries (Stojčić et al. 2019; Liu 2019). By instance, the both MCDM and FIS approaches have been widely used in the evaluation of Indian iron and steel industry supplier's sustainability performance (Jain et al. 2020). The obtained results were then used to make a framework for sustainable supplier selection which can rank the top two Indian suppliers (Jain et al. 2020).

2. Problem definition and proposed approach

Mines act as the economic core in developed countries and as the driving force in developing countries. The availability of mines in any country is considered as an economic support of that country and has a significant impact on its economic growth. Iran also has various mines due to its appropriate geographical location. In the past, mining and its affiliated industries aimed at generating wealth and creating job opportunities. However, recently, with the introduction of environmental issues and sustainable development, the environmental dimension has also received attention in addition to the economic and social dimension. The continuous improvement and sustainability in the mining industry is contingent upon the discovery of the effective factors in this field and control of them. The application of a measurement instrument for the identification of effective criteria and evaluation of mining performance from three economic, environmental, and social dimensions can lead to increased sustainability in this area. Therefore, this paper aims at developing a hybrid approach based on fuzzy BWM and FIS to evaluate the performance of mines under uncertainty conditions. This approach has been presented in the following:

Step 1: The criteria for evaluating the mining industry are specified and decided upon in this step in line with the related literature and expert opinion. As the basis of mine evaluation is sustainability, the criteria for such an evaluation should be set in such a way that economic, environmental, and social dimensions can be covered. It is assumed that the number of n criteria is determined (CR_1, CR_2, ..., CR_n).

Step 2: This step is devoted to the selection of the worst and best criteria based on expert opinion. It should be mentioned that the best criterion is the most important one while the one with the lowest degree off importance is considered as the worst criterion. The best and worst criteria are denoted by CR_B and CR_W, respectively.

Step 3: This step is allocated to making a pairwise comparison by experts between the best criterion and the other ones by means of linguistic words as shown in Table 1. Thereafter, the best-to-others vector gets specified by the replacement of corresponding triangular fuzzy numbers. The resultant fuzzy best-to-others vector is presented as:

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

where the fuzzy best-to-others vector is represented by $\tilde{D}_B$; the fuzzy preference of the best criterion is denoted by $\tilde{d}_{Bj}$, and the best criterion is also represented by CR_{Bj} ($j = 1, 2, ..., n$). Then, one can notice that $\tilde{d}_{BB} = (1,1,1)$.

Table 1. Linguistic terms for pairwise comparison (Kannan et al. 2020)

Tabela 1. Terminy językowe do porównań parami

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

Step 4: Similar to Step 3, this step also goes to experts and request them to make a comparison between the worst criterion and the other ones using the linguistic concepts, as

shown in Table 1. Afterwards, the corresponding triangular fuzzy values are replaced to obtain the Others-to-Worst vector. Below is the vector:

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

Where $\tilde{d}_{jW}$ indicates the fuzzy preference of the criterion *i*over the worst criterion CR_W; $\tilde{D}_W$ represents the fuzzy others-to-worst vector; and $i = 1, 2, ..., n$. Thus, it is possible to understand that $\tilde{d}_{WW} = (1,1,1)$.

Step 5: Here, the weights of the criteria are calculated by solving the fuzzy mathematical model presented below.

$$\begin{aligned}
&Min\, Max \left\{ \left| \frac{\tilde{\theta}_B}{\tilde{\theta}_j} - \tilde{d}_{Bj} \right|, \left| \frac{\tilde{\theta}_j}{\tilde{\theta}_W} - \tilde{d}_{jW} \right| \right\} \\
&St: \\
&\sum_{j=1}^{n} R(\tilde{\theta}_j) = 1 \\
&\theta_j^p \le \theta_j^m \le \theta_j^o \\
&\theta_j^p \ge 0 \\
&j = 1, 2, ..., n
\end{aligned} \tag{3}$$

In addition, the weight of the *j-th* criterion is shown by $\tilde{\theta}_j = (\theta_j^p, \theta_j^m, \theta_j^o)$ in which, θ_j^p, θ_j^m and θ_j^o are the triangular fuzzy numbers representing the pessimistic, most possible, and optimistic values, respectively. As a result, the following fuzzy numbers will be obtained:

$$\begin{aligned}
\tilde{\theta}_B &= (\theta_B^p, \theta_B^m, \theta_B^o) \\
\tilde{\theta}_W &= (\theta_W^p, \theta_W^m, \theta_W^o) \\
\tilde{d}_{Bj} &= (d_{Bj}^p, d_{Bj}^m, d_{Bj}^o) \\
\tilde{d}_{jW} &= (d_{jW}^p, d_{jW}^m, d_{jW}^o)
\end{aligned}$$

Replacing $\tilde{\delta} = Max \left\{ \left| \frac{\tilde{\theta}_B}{\tilde{\theta}_j} - \tilde{d}_{Bj} \right|, \left| \frac{\tilde{\theta}_j}{\tilde{\theta}_W} - \tilde{d}_{jW} \right| \right\}$ in Eq. (3), the following nonlinear model is obtained.

$$\begin{aligned}
&Min\ \tilde{\delta} \\
&St: \\
&\left|\frac{\tilde{\theta}_B}{\tilde{\theta}_j} - \tilde{d}_{Bj}\right| \le \tilde{\delta} && \forall j \\
&\left|\frac{\tilde{\theta}_j}{\tilde{\theta}_W} - \tilde{d}_{jW}\right| \le \tilde{\delta} && \forall j \\
&\sum_j R(\tilde{\theta}_j) = 1 \\
&\theta_j^p \le \theta_j^m \le \theta_j^o \\
&\theta_j^p \ge 0 \\
&j = 1, 2, \ldots, n
\end{aligned} \tag{4}$$

where $\tilde{\delta} = (\delta^p, \delta^m, \delta^o)$. Assuming $\tilde{\delta}^* = (\delta^*, \delta^*, \delta^*)$ and $\delta^* \le \delta^p$, the following model will be obtained:

$$\begin{aligned}
&Min\ \delta^* \\
&St: \\
&\left|\frac{(\theta_B^p, \theta_B^m, \theta_B^o)}{(\theta_j^p, \theta_j^m, \theta_j^o)} - (d_{Bj}^p, d_{Bj}^m, d_{Bj}^o)\right| \le (\delta^*, \delta^*, \delta^*) && \forall j \\
&\left|\frac{(\theta_j^p, \theta_j^m, \theta_j^o)}{(\theta_W^p, \theta_W^m, \theta_W^o)} - (d_{jW}^p, d_{jW}^m, d_{jW}^o)\right| \le (\delta^*, \delta^*, \delta^*) && \forall j \\
&\sum_j \frac{\theta_j^p + 4 \times \theta_j^m + \theta_j^o}{6} = 1 \\
&\theta_j^p \le \theta_j^m \le \theta_j^o \\
&\theta_j^p \ge 0 \\
&j = 1, 2, \ldots, n
\end{aligned} \tag{5}$$

By implementing the model in the optimization software, one can obtain the weight of each criterion and δ^*.

Step 6: Here, one may calculate the consistency ratio (*CR)* by means of the consistency index (*CI*), as shown in Table 2 and Eq. (6). As the consistency ratio is nearer to zero, the consistency will increase more.

$$CR = \frac{\delta^*}{CI} \tag{6}$$

Table 2. Consistency index for fuzzy BWM (Kannan et al. 2020)

Tabela 2. Wskaźnik spójności dla rozmytego BWM

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)
CI	3	3.8	5.29	6.69	8.04

Step 7: This step is an attempt to evaluate the mine in terms of each sub-criterion. To this end, related experts are given a questionnaire in order to assign a score for the mine performance with regard to each sub-criterion by means of linguistic concepts as in Table 3. Then, the average score assigned by experts is regarded as the evaluation score for the mine in terms of each sub-criterion. At the end, the score of each criterion, namely economic, environmental, and social criteria is also obtained by calculating the sum of the weights of each sub-criterion in the evaluated values. These processes are followed for each criterion independently. Eq. (7) represents such calculations.

$$Score = \sum_{j=1}^{n} \tilde{\theta}_j \cdot \tilde{X}_j \tag{7}$$

In which $\tilde{X}_j = (X_j^p, X_j^m, X_j^o)$ indicates the mean value resulting from evaluating the mine under study in terms of sub-criterion j thus, the following relation holds true:

$$Fuzzy\,score = \sum_{j=1}^{n} (\theta_j^p, \theta_j^m, \theta_j^o) \otimes (X_j^p, X_j^m, X_j^o) = \sum_{j=1}^{n} (\theta_j^p \cdot X_j^p, \theta_j^m \cdot X_j^m, \theta_j^o \cdot X_j^o) \tag{8}$$

As a result, the mine score with regard to the criteria is computed with fuzzy numbers. Then, the performance evaluation gets difuzzified via Eq. (9) (Kannan et al. 2020).

$$Defuzzy\,score = \sum_{j=1}^{n} \frac{(\theta_j^p \cdot X_j^p) + 4 \cdot (\theta_j^m \cdot X_j^m) + (\theta_j^o \cdot X_j^o)}{6} \tag{9}$$

Table 3. Linguistic terms for evaluating alternatives

Tabela 3. Terminy językowe do oceny rozwiązań alternatywnych

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)

Step 8: In this step, the fuzzy inference system is developed. In doing so, the input and output variables of this system should be first recognized. In the previous step, the score of the studied mine was calculated for each of the economic, environmental, and social criteria separately. These criteria are considered as the input variables and the final score of mine is defined as the output variable.

Three membership functions, i.e. low, mid, and high constitute the input variables, while five membership functions, i.e. very low, low, mid, high, and very high are the constituents of the output variable.In order to form a fuzzy inference system, the input and output variables should be first defined in the system and their membership functions should be then determined. This operation is explained in detail in the case study section.

Step 9: This step is dedicated to the determination of the fuzzy inference rules with the help of relevant experts for establishing an interconnection between the input and output variables.

Since the system consists of three input variables and the input variables contain three membership functions, the number of 3^3 (89) rules should be defined for the fuzzy inference system. Hence, the fuzzy inference rules already extracted from the expert knowledge of are inserted in the intended system. In this way, the fuzzy inference system is developed.

Step 10: In this step, the final score of the desired mine is calculated. For this purpose, the values calculated in step 7 for each criterion are inserted into the fuzzy inference system as inputs and the final score of the mine is then calculated.

3. Case study

In 1927, some engineering plans were drawn up to bring theiron smelting industry to the northern part of Iranin order to be able to have the train rail tracks domestically produced. Today, iron and steel industry are the most important industrial section of Iran's economy. In recent years, this mentioned industry has experienced a high rate of growth. In 2019, Iran overall produced 31.9 million tons of steel. A 30 percent increase was recorded in compare to 2018 statistics which was nearly 24 million tons of steel production. Iran's annual steel production is planned to reach 45 million tons in 2021. The third largest steel-producer company in Iran, i.e, Khorasan Steel Complex (KSC) has been chosen for this study. The case study has been located in an area of 1,400 hectares in 15 km of the North-West of Neishabur-Firouzeh Road, Khorasan-e-Razavi province, eastern Iran. Overall 16 different units are currently active in Khorasan Steel Complex, including four main units of direct iron reduction, smelting, casting, and rolling as well as some units for peripheral, and support. The mentioned units produce 6.1 million tons of steel per year (Hossein Pour et al. 2014).

Table 4. Evaluation Criteria of the Intended Industry

Tabela 4. Kryteria oceny przewidywanej branży

Aspect	Criteria	Reference
Economic	Economic benefits (EC1)	Shields 2005
	Production capacity (EC2)	Bafrooei et al. 2014; Beyene et al. 2020
	Logistics (EC3)	Saeidi et al. 2017
	Technological and financial capability (EC4)	Mina et al. 2014; Luo et al. 2019
	Research and development (EC5)	Salimi and Rezaei 2018; Guarnieri and Trojan 2019
	Flexibility (EC6)	Awasthi et al. 2018
Environmental	Use of energy (EN1)	Kusi-Sarpong et al. 2016; Pishchulov et al. 2019
	Environmental management technologies and knowledge (EN2)	Kusi-Sarpong et al. 2016
	Waste management (EN3)	Awasthi et al. 2018; Pishchulov et al. 2019
	Air emissions (EN4)	Govindan et al. 2019; Jozanikohan 2017
	Environmental standards and regulations (EN5)	Kannan et al. 2020; Awasthi et al. 2018; Azimifard et al. 2018
Social	Occupational health and safety systems (SO1)	Pishchulov et al. 2019; Bai et al. 2019
	Job creation (SO2)	Kannan et al. 2020
	The rights and interests of employees (SO3)	Kannan et al. 2020; Guarnieri and Trojan 2019; Awasthi et al. 2018
	The rights of stockholders (SO4)	Kannan et al. 2020; Guarnieri and Trojan 2019; Awasthi et al. 2018
	Child and forced labour (SO5)	Pishchulov et al. 2019

The implementation process of the proposed approach in the case study is presented as follows:

Step 1: In this step, the literature pertaining to performance evaluation in the mining industry and similar fields was reviewed and, thereby, a series of criteria were selected for the evaluation of the intended industry from three economic, environmental, and social aspects based on expert opinion. It is noteworthy that experts took advantage of brainstorming method to select the appropriate criteria. In Table 4, the industry evaluation criteria have been presented. It should be noted that the dependency between criteria is very low as per expert opinion, so it can be overlooked. Therefore, there is no need to calculate the dependency in the weighting process.

Step 2: In this step, the experts determine the best and worst criteria. The best and worst criteria are presented in Table 5 based on expert opinion.

Table 5. The best and the worst criteria

Tabela 5. Kryteria najlepsze i najgorsze

	The best	The worst
Economic sub-criteria	Economic benefits	Flexibility
Environmental sub-criteria	Environmental management technologies and knowledge	Use of energy
Social sub-criteria	Occupational health and safety systems	Job creation

Step 3: In this step, the experts are requested to compare the best criteria with other criteria (pairwise comparisons) using Table 1. In the following, the fuzzy best-to-others vectors have been listed for economic, environmental, and social criteria, respectively.

- Economic: $\tilde{D}_{B-EC}=\left[(1,1,1),\left(\frac{2}{3},1,\frac{3}{2}\right),\left(\frac{3}{2},2,\frac{5}{2}\right),\left(\frac{2}{3},1,\frac{3}{2}\right),\left(\frac{3}{2},2,\frac{5}{2}\right),\left(\frac{5}{2},3,\frac{7}{2}\right)\right]$
- Environmental: $\tilde{D}_{B-EN}=\left[\left(\frac{5}{2},3,\frac{7}{2}\right),(1,1,1),\left(\frac{2}{3},1,\frac{3}{2}\right),\left(\frac{2}{3},1,\frac{3}{2}\right),\left(\frac{3}{2},2,\frac{5}{2}\right)\right]$
- Social: $\tilde{D}_{B-SC}=\left[(1,1,1),\left(\frac{7}{2},4,\frac{9}{2}\right),\left(\frac{2}{3},1,\frac{3}{2}\right),\left(\frac{3}{2},2,\frac{5}{2}\right),\left(\frac{5}{2},3,\frac{7}{2}\right)\right]$

Step 4: In this step, it is asked from experts to make a pairwise comparison between the other criteria and the worst one using Table 1. In the following, the fuzzy others-to-worst vectors have been shown for economic, environmental, and social criteria, respectively.

- Economic: $\tilde{D}_{W-EC}=\left[\left(\frac{5}{2},3,\frac{7}{2}\right),\left(\frac{3}{2},2,\frac{5}{2}\right),\left(\frac{2}{3},1,\frac{3}{2}\right),\left(\frac{3}{2},2,\frac{5}{2}\right),\left(\frac{2}{3},1,\frac{3}{2}\right),(1,1,1)\right]$
- Environmental: $\tilde{D}_{W-EN}=\left[(1,1,1),\left(\frac{5}{2},3,\frac{7}{2}\right),\left(\frac{3}{2},2,\frac{5}{2}\right),\left(\frac{3}{2},2,\frac{5}{2}\right),\left(\frac{2}{3},1,\frac{3}{2}\right)\right]$

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

Step 5: In this step, the non-linear model has been developed using the fuzzy others-to--worst vector, the fuzzy best-to-others vector, and Eq. (5) and, then the weights of criteria have been calculated. For example, the non-linear model developed with regard to the criteria relating to economic aspect is presented as follows:

min δ^*

St:

$$\theta_1^p-\frac{2}{3}\cdot\theta_2^o\le\delta^*\cdot\theta_2^o;\quad \theta_1^p-\frac{2}{3}\cdot\theta_2^o\ge-\delta^*\cdot\theta_2^o;\quad \theta_2^p-\frac{3}{2}\cdot\theta_6^o\le\delta^*\cdot\theta_6^o;\quad \theta_2^p-\frac{3}{2}\cdot\theta_6^o\ge-\delta^*\cdot\theta_6^o$$

$$\theta_1^m-\theta_2^m\le\delta^*\cdot\theta_2^m;\quad \theta_1^m-\theta_2^m\ge-\delta^*\cdot\theta_2^m;\quad \theta_2^m-2\cdot\theta_6^m\le\delta^*\cdot\theta_6^m;\quad \theta_2^m-2\cdot\theta_6^m\ge-\delta^*\cdot\theta_6^m$$

$$\theta_1^o-\frac{3}{2}\cdot\theta_2^p\le\delta^*\cdot\theta_2^p;\quad \theta_1^o-\frac{3}{2}\cdot\theta_2^p\ge-\delta^*\cdot\theta_2^p;\quad \theta_2^o-\frac{5}{2}\cdot\theta_6^p\le\delta^*\cdot\theta_6^p;\quad \theta_2^o-\frac{5}{2}\cdot\theta_6^p\ge-\delta^*\cdot\theta_6^p$$

$$\theta_1^p-\frac{3}{2}\cdot\theta_3^o\le\delta^*\cdot\theta_3^o;\quad \theta_1^p-\frac{3}{2}\cdot\theta_3^o\ge-\delta^*\cdot\theta_3^o;\quad \theta_3^p-\frac{2}{3}\cdot\theta_6^o\le\delta^*\cdot\theta_6^o;\quad \theta_3^p-\frac{2}{3}\cdot\theta_6^o\ge-\delta^*\cdot\theta_6^o$$

$$\theta_1^m-2\cdot\theta_3^m\le\delta^*\cdot b_3^w;\quad \theta_1^m-2\cdot\theta_3^m\ge-\delta^*\cdot\theta_3^m;\quad \theta_3^m-\theta_6^m\le\delta^*\cdot\theta_6^m;\quad \theta_3^m-\theta_6^m\ge-\delta^*\cdot\theta_6^m$$

$$\theta_1^o-\frac{5}{2}\cdot\theta_3^p\le\delta^*\cdot\theta_3^p;\quad \theta_1^o-\frac{5}{2}\cdot\theta_3^p\ge-\delta^*\cdot\theta_3^p;\quad \theta_3^o-\frac{3}{2}\cdot\theta_6^p\le\delta^*\cdot\theta_6^p;\quad \theta_3^o-\frac{3}{2}\cdot\theta_6^p\ge-\delta^*\cdot\theta_6^p$$

$$\theta_1^p-\frac{3}{2}\cdot\theta_4^o\le\delta^*\cdot\theta_4^o;\quad \theta_1^p-\frac{3}{2}\cdot\theta_4^o\ge-\delta^*\cdot\theta_4^o;\quad \theta_4^p-\frac{3}{2}\cdot\theta_6^o\le\delta^*\cdot\theta_6^o;\quad \theta_4^p-\frac{3}{2}\cdot\theta_6^o\ge-\delta^*\cdot\theta_6^o$$

$$\theta_1^m-\theta_4^m\le\delta^*\cdot\theta_4^w;\quad \theta_1^m-\theta_4^m\ge-\delta^*\cdot\theta_4^m;\quad \theta_4^m-2\cdot\theta_6^m\le\delta^*\cdot\theta_6^m;\quad \theta_4^m-2\cdot\theta_6^m\ge-\delta^*\cdot\theta_6^m$$

$$\theta_1^o-\frac{3}{2}\cdot\theta_4^p\le\delta^*\cdot\theta_4^p;\quad \theta_1^o-\frac{3}{2}\cdot\theta_4^p\ge-\delta^*\cdot\theta_4^p;\quad \theta_4^o-\frac{5}{2}\cdot\theta_6^p\le\delta^*\cdot\theta_6^p;\quad \theta_4^o-\frac{5}{2}\cdot\theta_6^p\ge-\delta^*\cdot\theta_6^p$$

$$\theta_1^p-\frac{3}{2}\cdot\theta_5^o\le\delta^*\cdot\theta_5^o;\quad \theta_1^p-\frac{3}{2}\cdot\theta_5^o\ge-\delta^*\cdot\theta_5^o;\quad \theta_5^p-\frac{2}{3}\cdot\theta_6^o\le\delta^*\cdot\theta_6^o;\quad \theta_5^p-\frac{2}{3}\cdot\theta_6^o\ge-\delta^*\cdot\theta_6^o$$

$$\theta_1^m-2\cdot\theta_5^m\le\delta^*\cdot\theta_5^m;\quad \theta_1^m-2\cdot\theta_5^m\ge-\delta^*\cdot\theta_5^m;\quad \theta_5^m-\theta_6^m\le\delta^*\cdot\theta_6^m;\quad \theta_5^m-\theta_6^m\ge-\delta^*\cdot\theta_6^m$$

$$\theta_1^o-\frac{5}{2}\cdot\theta_5^p\le\delta^*\cdot\theta_5^p;\quad \theta_1^o-\frac{5}{2}\cdot\theta_5^p\ge-\delta^*\cdot\theta_5^p;\quad \theta_5^o-\frac{3}{2}\cdot\theta_6^p\le\delta^*\cdot\theta_6^p;\quad \theta_5^o-\frac{3}{2}\cdot\theta_6^p\ge-\delta^*\cdot\theta_6^p$$

$$\theta_1^p-\frac{5}{2}\cdot\theta_6^o\le\delta^*\cdot\theta_6^o;\quad \theta_1^p-\frac{5}{2}\cdot\theta_6^o\ge-\delta^*\cdot\theta_6^o;$$

$$\theta_1^m-3\cdot\theta_6^m\le\delta^*\cdot\theta_6^m;\quad \theta_1^m-3\cdot\theta_6^m\ge-\delta^*\cdot\theta_6^m;$$

$$\theta_1^o-\frac{7}{2}\cdot\theta_6^p\le\delta^*\cdot\theta_6^p;\quad \theta_1^o-\frac{7}{2}\cdot\theta_6^p\ge-\delta^*\cdot\theta_6^p;$$

$$\frac{1}{6}\cdot(\theta_1^p+\theta_2^p+\theta_3^p+\theta_4^p+\theta_5^p+\theta_6^p)+\frac{2}{3}\cdot(\theta_1^m+\theta_2^m+\theta_3^m+\theta_4^m+\theta_5^m+\theta_6^m)+\frac{1}{6}\cdot(\theta_1^o+\theta_2^o+\theta_3^o+\theta_4^o+\theta_5^o+\theta_6^o)=1$$

$$\theta_1^p\le\theta_1^m\le\theta_1^o;\quad \theta_2^p\le\theta_2^m\le\theta_2^o;\quad \theta_3^p\le\theta_3^m\le\theta_3^o;$$

$$\theta_4^p\le\theta_4^m\le\theta_4^o;\quad \theta_5^p\le\theta_5^m\le\theta_5^o;\quad \theta_6^p\le\theta_6^m\le\theta_6^o$$

$$\theta_1^p,\theta_2^p,\theta_3^p,\theta_4^p,\theta_5^p,\theta_6^p>0\quad\text{and}\quad\delta^*\ge0$$

Following the usage of this model in GAMS software by means of BARON solver, the fuzzy weights of criteria have been calculated. The fuzzy weights of criteria and optimal value of δ^* have been shown in Table 6.

Table 6. The fuzzy weights of criteria

Tabela 6. Rozmyte wagi kryteriów

Aspect	Criteria	Weight			δ^*
		θ_j^p	θ_j^m	θ_j^o	
Economic	EC1	0.249	0.253	0.297	0.278
	EC2	0.170	0.195	0.258	
	EC3	0.111	0.12	0.139	
	EC4	0.170	0.195	0.258	
	EC5	0.111	0.120	0.139	
	EC6	0.089	0.092	0.108	
Environmental	EN1	0.098	0.105	0.119	0.299
	EN2	0.279	0.289	0.339	
	EN3	0.189	0.223	0.301	
	EN4	0.189	0.223	0.301	
	EN5	0.130	0.135	0.160	
Social	SO1	0.299	0.338	0.349	0.264
	SO2	0.081	0.089	0.094	
	SO3	0.228	0.272	0.301	
	SO4	0.155	0.192	0.236	
	SO5	0.097	0.116	0.132	

Step 6: Here, Eq. (6) and Table 2 have been used to compute the consistency ratios, which were obtained equal to 0.045, 0.033, and 0.042 for environmental, social, and economic criteria, respectively. Therefore, the values of consistency ratios are near to zero for each of the pairwise comparisons and the obtained weights are verified.

Step 7: In this step, experts evaluate the performance of the industry under study for each criterion through the linguistic terms presented in Table 3. In doing so, 8 experts have been asked to use their knowledge and score the criteria. In Table 7, the demographic profile of experts is presented. Moreover, the score of each criterion assigned by each expert to the organization under study is shown in Table 9. In Table 8, the mean value of the experts' per criterion has been shown for the purpose of evaluating the industry under study.

Table 7. Demographic profile of experts

Tabela 7. Średnia opinii ekspertów dla każdego kryterium

Expert	Gender		Work experience (year)	Job position	Graduate degree	Undergraduate degree
	Male	Female				
Expert 1	x		15	Quality control manager	x	
Expert 2	x		9	Production manager		x
Expert 3	x		7	Sales manager	x	
Expert 4	x		4	Quality assurance expert		x
Expert 5	x		4	Purchasing expert		x
Expert 6		x	8	Purchasing manger	x	
Expert 7		x	7	Production line manager	x	
Expert 8		x	3	Quality control expert		x

Table 8. Average of expert opinion for each criterion

Tabela 8. Ocena przewidywanej branży dla każdego aspektu

Sub-criteria	X_j^p	X_j^m	X_j^o
EC1	0.6375	0.7375	0.8375
EC2	0.5625	0.6625	0.7625
EC3	0.625	0.725	0.825
EC4	0.5375	0.6375	0.7375
EC5	0.4125	0.5125	0.6125
EC6	0.4625	0.5625	0.6625
EN1	0.2625	0.3625	0.4625
EN2	0.2875	0.3875	0.4875
EN3	0.4625	0.5625	0.6625
EN4	0.2375	0.3375	0.4375
EN5	0.5125	0.6125	0.7125
SO1	0.4625	0.5625	0.6625
SO2	0.35	0.45	0.55
SO3	0.375	0.475	0.575
SO4	0.6	0.7	0.8
SO5	0.4125	0.5	0.5875

Table 9. Expert opinion for each criterion

Tabela 9. Ekspertyza dla każdego kryterium

	Expert 1			Expert 2			Expert 3			Expert 4			Expert 5			Expert 6			Expert 7			Expert 8		
EC1	0.6	0.7	0.8	0.6	0.7	0.8	0.6	0.7	0.8	0.7	0.8	0.9	0.7	0.8	0.9	0.7	0.8	0.9	0.6	0.7	0.8	0.6	0.7	0.8
EC2	0.7	0.8	0.9	0.6	0.7	0.8	0.5	0.6	0.7	0.6	0.7	0.8	0.6	0.7	0.8	0.4	0.5	0.6	0.5	0.6	0.7	0.6	0.7	0.8
EC3	0.6	0.7	0.8	0.6	0.7	0.8	0.7	0.8	0.9	0.7	0.8	0.9	0.5	0.6	0.7	0.7	0.8	0.9	0.6	0.7	0.8	0.6	0.7	0.8
EC4	0.6	0.7	0.8	0.5	0.6	0.7	0.6	0.7	0.8	0.5	0.6	0.7	0.5	0.6	0.7	0.6	0.7	0.8	0.5	0.6	0.7	0.5	0.6	0.7
EC5	0.4	0.5	0.6	0.5	0.6	0.7	0.4	0.5	0.6	0.4	0.5	0.6	0.3	0.4	0.5	0.4	0.5	0.6	0.5	0.6	0.7	0.4	0.5	0.6
EC6	0.5	0.6	0.7	0.5	0.6	0.7	0.5	0.6	0.7	0.4	0.5	0.6	0.5	0.6	0.7	0.5	0.6	0.7	0.4	0.5	0.6	0.4	0.5	0.6
EN1	0.2	0.3	0.4	0.3	0.4	0.5	0.2	0.3	0.4	0.3	0.4	0.5	0.2	0.3	0.4	0.4	0.5	0.6	0.2	0.3	0.4	0.3	0.4	0.5
EN2	0.2	0.3	0.4	0.4	0.5	0.6	0.2	0.3	0.4	0.4	0.5	0.6	0.3	0.4	0.5	0.2	0.3	0.4	0.3	0.4	0.5	0.3	0.4	0.5
EN3	0.4	0.5	0.6	0.6	0.7	0.8	0.4	0.5	0.6	0.4	0.5	0.6	0.5	0.6	0.7	0.4	0.5	0.6	0.5	0.6	0.7	0.5	0.6	0.7
EN4	0.3	0.4	0.5	0.2	0.3	0.4	0.2	0.3	0.4	0.3	0.4	0.5	0.2	0.3	0.4	0.2	0.3	0.4	0.3	0.4	0.5	0.2	0.3	0.4
EN5	0.5	0.6	0.7	0.4	0.5	0.6	0.5	0.6	0.7	0.6	0.7	0.8	0.5	0.6	0.7	0.6	0.7	0.8	0.5	0.6	0.7	0.5	0.6	0.7
SO1	0.5	0.6	0.7	0.5	0.6	0.7	0.5	0.6	0.7	0.5	0.6	0.7	0.5	0.6	0.7	0.5	0.6	0.7	0.5	0.6	0.7	0.2	0.3	0.4
SO2	0.4	0.5	0.6	0.4	0.5	0.6	0.5	0.6	0.7	0.3	0.4	0.5	0.3	0.4	0.5	0.3	0.4	0.5	0.3	0.4	0.5	0.3	0.4	0.5
SO3	0.3	0.4	0.5	0.5	0.6	0.7	0.3	0.4	0.5	0.5	0.6	0.7	0.3	0.4	0.5	0.5	0.6	0.7	0.3	0.4	0.5	0.3	0.4	0.5
SO4	0.6	0.7	0.8	0.6	0.7	0.8	0.6	0.7	0.8	0.7	0.8	0.9	0.7	0.8	0.9	0.6	0.7	0.8	0.4	0.5	0.6	0.6	0.7	0.8
SO5	0.4	0.5	0.6	0.4	0.5	0.6	0.4	0.5	0.6	0.4	0.5	0.6	0.4	0.5	0.6	0.4	0.5	0.6	0.4	0.5	0.6	0.5	0.6	0.7

Then, it is turn to the calculation of the fuzzy and defuzzified scores of the industry with regard to each aspect using Eq. (8) and Eq. (9), as shown in Table 10:

Table 10. Score of the intended industry for each aspect

Tabela 10. Wynik przewidywanej branży dla każdego aspektu

Aspect	Fuzzy score	Defuzzified score
Economic	(0.5021, 0.6403, 0.9071)	0.6618
Environmental	(0.3049, 0.4334, 0.6654)	0.4507
Social	(0.3852, 0.5518, 0.7223)	0.5524

Step 8: In this step, a system is developed for calculating the final score of the industry under study using the fuzzy inference system already proposed by Govindan et al. (Govindan et al. 2020). In this regard, one may initially determined the input and output variables of the fuzzy inference system where the economic, environmental, and social are considered as the input variables while the final score of the industry is regarded as the output variable.

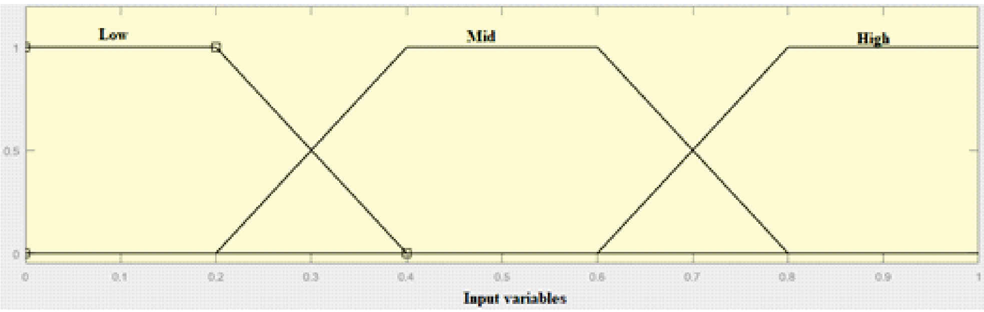

Fig. 1. Membership functions of input variables

Rys. 1. Funkcje przynależności zmiennych wejściowych

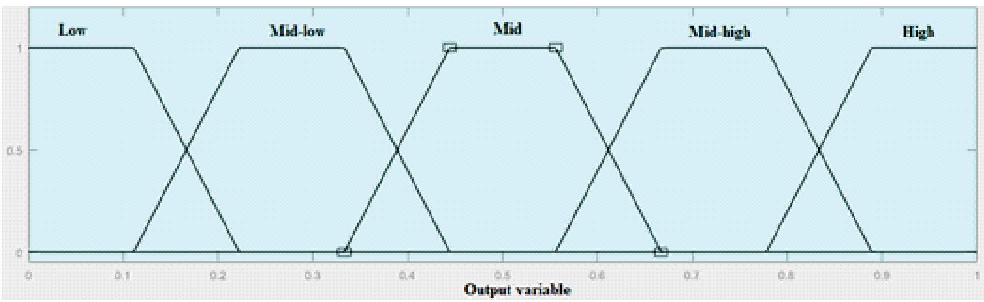

Fig. 2. Membership functions of output variable

Rys. 2. Funkcje przynależności zmiennych wyjściowych

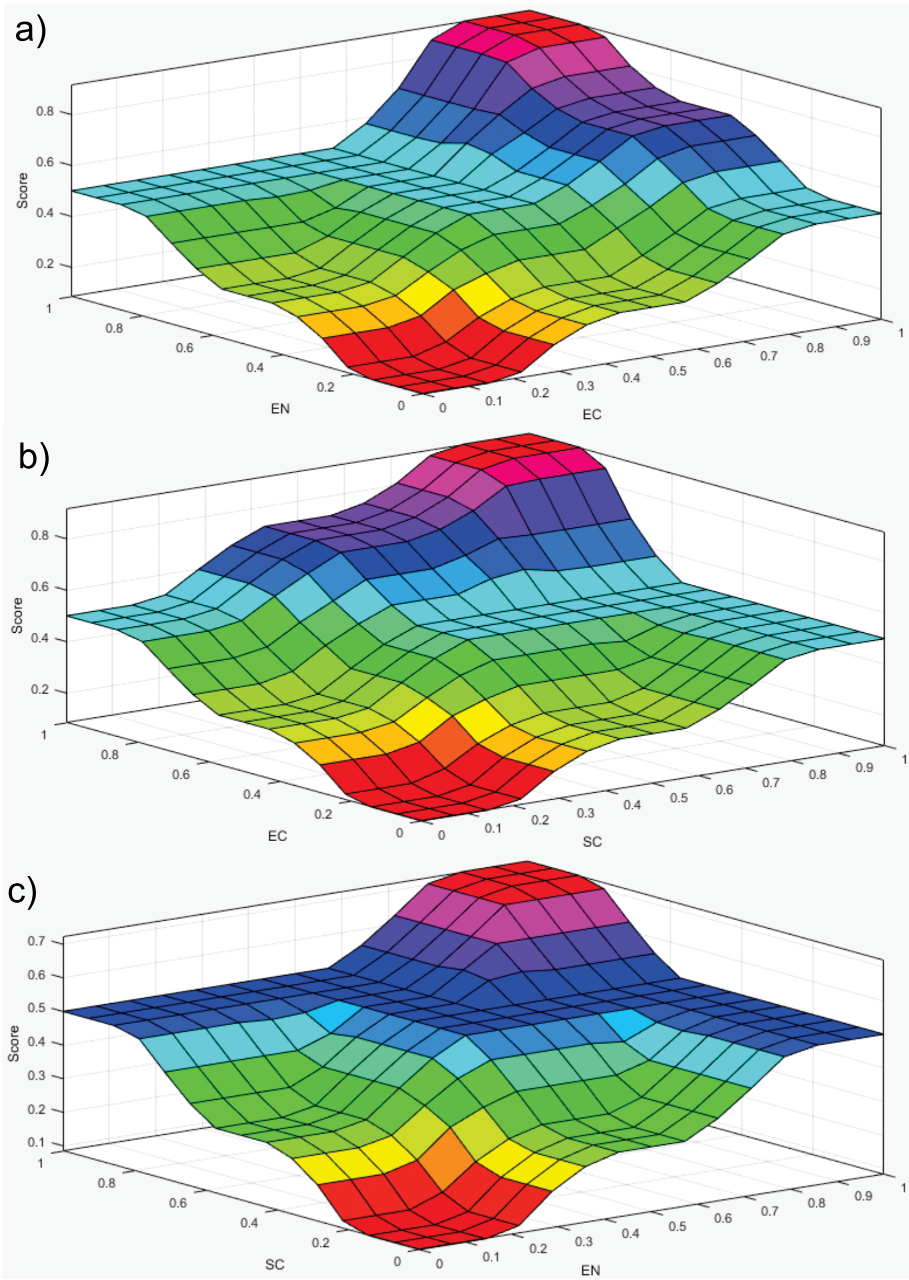

Fig. 3. The fuzzy inference rules in the three-dimensional space
a) relationship among economic and environmental aspects, b) relationship among economic and social aspects, c) relationship among environmental and social aspects

Rys. 3. Zasady wnioskowania rozmytego w przestrzeni trójwymiarowej
a) związek między aspektami ekonomicznymi i środowiskowymi, b) relacje między aspektami ekonomicznymi i społecznymi, c) relacje między aspektami środowiskowymi i społecznymi

There are three membership functions, entitled low, mid, and high in the input variables whereas there are five membership functions in the output variables. The membership functions of the input variables are shown in Figure 1 and those of the output variable have been presented in Figure 2.

Step 9: Here, experts determined the fuzzy inference rules. It should be mentioned that the fuzzy inference system consist of three membership functions and three input variables, which has been regarded for each of the input variables; thus, every group of individuals will have the number of $3^3 = 27$ fuzzy inference rules. When the fuzzy inference rules are extracted and implemented in MATLAB R2019a software by means of fuzzy inference systemEditor GUI toolbox, the association between the output and input variables can be observed in the three-dimensional space. The fuzzy inference rules are also presented at the three-dimensional space in Figure 3.

Step 10: In this step, the final score of the industry under study is calculated by the proposed fuzzy inference system. To this end, in the rule reviewer box of proposed fuzzy inference system, the economic, environmental, and social values already calculated in step 7 are submitted to the system as the inputs. Then, the final score is calculated as the output. The final score of the desired industry has been evaluated equal to 0.572. Based on the classification presented in Figure 2, the score obtained for the industry is placed in the Mid and Mid-high class. If this industry is able to increase its performance by 0.095, then it will exit the Mid class and will be completely placed in the Mid-high class. In general, the industry under study should focus on the criteria with both high weights and low evaluated scores to increase its performance evaluation score. For example, as shown in Table 6, the criterion named environmental management technologies and knowledge has a high weight, but it has a low evaluation score according to the results presented in Table 7. Therefore, the industry under study can increase the environmental performance by focusing on this criterion and its enhancement, which may lead to an increase in the final score of the intended industry.

Conclusion

In this paper, a practical approach was developed through the integration of fuzzy BWM and FIS methods in order to evaluate the performance of mining industries while all three aspects of sustainability, namely economic, environmental, and social ones were taken into consideration. In the proposed approach, evaluation criteria were extracted from the triple aspects of sustainability and the performance of the desired industry was evaluated in terms of each of the criteria. Fuzzy BWM was used to determine the weights of the criteria and, then, the industry score was calculated separately for each of the triple aspects of sustainability. Finally, an FIS was designed based on expert knowledge in a steel complex in Iran and the final score of the industry was then calculated. It should be mentioned that the economic, environmental, and social scores of the intended industry were considered as the inputs and the final score was regarded as the FIS output. The results of the proposed FIS showed that the industry has a moderate to high performance and, thereby, some relevant suggestions were proposed to improve its performance.

REFERENCES

Ahmadi et al. 2017 – Ahmadi, H.B., Kusi-Sarpong, S. and Rezaei, J. 2017. Assessing the social sustainability of supply chains using Best Worst Method. *Resources, Conservation and Recycling* 126, pp. 99–106.

Allan, R. 1995. Introduction: sustainable mining in the future. *Journal of Geochemical Exploration* 52(1–2), pp. 1–4.

Anand et al. 2017 – Anand, A., Rufuss, D.D.W., Rajkumar, V. and Suganthi, L. 2017. Evaluation of sustainability indicators in smart cities for India using MCDM approach. *Energy Procedia* 141, pp. 211–215.

Asr et al. 2019 – Asr, E.T., Kakaie, R., Ataei, M. and Mohammadi, M.R.T. 2019. A Review of Studies on Sustainable Development in Mining Life Cycle. *Journal of Cleaner Production* 229, pp. 213–231.

Awasthi et al. 2018 – Awasthi, A., Govindan, K. and Gold, S. 2018. Multi-tier sustainable global supplier selection using a fuzzy AHP-VIKOR based approach. *International Journal of Production Economics* 195, pp. 106–117.

Azimifard et al. 2018 – Azimifard, A., Moosavirad, S. H. and Ariafar, S. 2018. Selecting sustainable supplier countries for Iran's steel industry at three levels by using AHP and TOPSIS methods. *Resources Policy* 57, pp. 30–44.

Bai et al. 2019 – Bai, C., Kusi-Sarpong, S., Badri Ahmadi, H. and Sarkis, J. 2019. Social sustainable supplier evaluation and selection: a group decision-support approach. *International Journal of Production Research* 57(22), pp. 7046–7067.

Bafrooei et al. 2014 – Bafrooei, A.A., Mina, H. and Ghaderi, S.F. 2014. A supplier selection problem in petrochemical industry using common weight data envelopment analysis with qualitative criteria. *International Journal of Industrial and Systems Engineering* 18(3), pp. 404–417.

Basu, A.J. and Kumar, U. 2004. Innovation and technology driven sustainability performance management framework (ITSPM) for the mining and minerals sector. *International Journal of Surface Mining* 18(2), pp. 135–149.

Beyene et al. 2020 – Beyene, E., Tefera, A.T., Muleta, D., Fantahun, S.K. and Wessel, G.M. 2020. Molecular identification and performance evaluation of wild yeasts from different Ethiopian fermented products. *Journal of Food Science and Technology* 57(9), pp. 3436–3444.

Botin, J.A. 2009. Sustainable Management of Mining Operations. Society for Mining, Metallurgy an Exploration. *Inc. Englewood, CO*.

Cerin, P. 2006. Bringing economic opportunity into line with environmental influence: A discussion on the Coase theorem and the Porter and van der Linde hypothesis. *Ecological Economics* 56(2), pp. 209–225.

Crowson, P. 1998. Mining and sustainable development: measurement and indicators. *Minerals and Energy* 13(1), pp. 27–33.

Dernbach, J.C. 1998. Sustainable development as a framework for national governance. *Case W. Res. L. Rev.* 49(1).

Dubiński, J. 2013. Sustainable development of mining mineral resources. *Journal of Sustainable Mining* 12(1), pp. 1–6.

Folchi, R. 2003. Environmental impact statement for mining with explosives: a quantitative method. *Proceedings of the annual conference on explosives and blasting technique* 2, pp. 285–296.

Fonseca et al. 2013 – Fonseca, A., McAllister, M.L. and Fitzpatrick, P. 2013. Measuring what? A comparative anatomy of five mining sustainability frameworks. *Minerals Engineering* 46, pp. 180–186.

Ghaedrahmati, R. and Doulati Ardejani, F. 2012. Environmental impact assessment of coal washing plant (Alborz-Sharghi–Iran). *Journal of Mining and Environment* 3(2), pp. 69–77.

Govindan et al. 2020 – Govindan, K., Mina, H., Esmaeili, A. and Gholami-Zanjani, S.M. 2020. An integrated hybrid approach for circular supplier selection and closed loop supply chain network design under uncertainty. *Journal of Cleaner Production* 242, 118317.

Govindan et al. 2020 – Govindan, K., Mina, H. and Alavi, B. 2020. A decision support system for demand management in healthcare supply chains considering the epidemic outbreaks: A case study of coronavirus disease 2019 (COVID-19). *Transportation Research Part E: Logistics and Transportation Review* 138, 101967.

Govindan et al. 2019 – Govindan, K., Jha, P.C., Agarwal, V. and Darbari, J.D. 2019. Environmental management partner selection for reverse supply chain collaboration: A sustainable approach. *Journal of environmental management* 236, pp. 784–797.

Guarnieri, P. and Trojan, F. 2019. Decision making on supplier selection based on social, ethical, and environmental criteria: A study in the textile industry. *Resources, Conservation and Recycling* 141, pp. 347–361.

Hartman, H.L. and Mutmansky, J.M. 2002. *Introductory mining engineering*. John Wiley & Sons.

Hossein Pour et al. 2014 – Hossein Pour, M., Lashkaripour, G. R. and Dehghan, P. 2014. Environmental pollution evaluation of steel plants for achieving sustainable development; case study: khorasan steel complex of Iran. *Journal of Biodiversity and Environmental Sciences* 4.

Jarvie-Eggart, M.E., ed. 2015. *Responsible Mining: Case Studies in Managing Social & Environmental Risks in the Developed World*. SME.

Jain et al. 2020 – Jain, N., Singh, A.R. and Upadhyay, R.K. 2020. Sustainable supplier selection under attractive criteria through FIS and integrated fuzzy MCDM techniques. *International Journal of Sustainable Engineering* 13(4).

Jozanikohan, G. 2017. On the development of a non-linear calibration relationship for the purpose of clay content estimation from the natural gamma ray log. *International Journal of Geo-Engineering* 8(1).

Kannan et al. 2020 – Kannan, D., Mina, H., Nosrati-Abarghooee, S. and Khosrojerdi, G. 2020. Sustainable circular supplier selection: A novel hybrid approach. *The Science of the Total Environment* 722, 137936.

Kauppinen, T. and Khajehzadeh, N. 2015. Sustainability in the exploration phase of mining: a Data Envelopment Analysis approach. *IFAC-PapersOnLine* 48(17), pp. 114–118.

Kusi-Sarpong et al. 2016 – Kusi-Sarpong, S., Sarkis, J. and Wang, X. 2016. Assessing green supply chain practices in the Ghanaian mining industry: A framework and evaluation. *International Journal of Production Economics* 181, pp. 325–341.

Lala et al. 2016 – Lala, A., Moyo, M., Rehbach, S. and Sellschop, R. 2016. Productivity in mining operations: Reversing the downward trend. *AusIMM Bulletin*, (Aug 2016), 46.

Leopold, L.B. 1971. *A procedure for evaluating environmental impact*. US Dept. of the Interior 28(2).

Learmont, D. 1997. Mining must show that it is sustainable. *Mining Engineering* 49(1), pp. 1–12.

Liu, N. 2019. Research on Evaluation of Coal Enterprises Sustainable Development. *IOP Conference Series: Earth and Environmental Science* 300(2).

Lu et al. 2018 – Lu, M.T., Hsu, C.C., Liou, J.J. and Lo, H.W. 2018. A hybrid MCDM and sustainability-balanced scorecard model to establish sustainable performance evaluation for international airports. *Journal of Air Transport Management* 71, pp. 9–19.

Luo et al. 2019 – Luo, S.Z., Liang, W.Z. and Xing, L.N. 2019. Selection of mine development scheme based on similarity measure under fuzzy environment. *Neural Computing and Applications* 32.

Marnika et al. 2015 – Marnika, E., Christodoulou, E. and Xenidis, A. 2015. Sustainable development indicators for mining sites in protected areas: tool development, ranking and scoring of potential environmental impacts and assessment of management scenarios. *Journal of Cleaner Production* 101, pp. 59–70.

Malek, J. and Desai, T.N. 2019. Prioritization of sustainable manufacturing barriers using Best Worst Method. *Journal of Cleaner Production* 226, pp. 589–600.

Mavi, R.K. and Standing, C. 2018. Critical success factors of sustainable project management in construction: A fuzzy DEMATEL-ANP approach. *Journal of cleaner production* 194, pp. 751–765.

McLellan et al. 2009 – McLellan, B.C., Corder, G.D., Giurco, D. and Green, S. 2009. Incorporating sustainable development in the design of mineral processing operations–Review and analysis of current approaches. *Journal of Cleaner Production* 17(16), pp. 1414–1425.

Mina et al. 2014 – Mina, H., Mirabedin, S.N. and Pakzad-Moghadam, S.H. 2014. An integrated fuzzy analytic network process approach for green supplier selection: a case study of petrochemical industry. *Management Science and Practice* 2(2), pp. 31–47.

Nuong et al. 2011 – Nuong, B.T., Kim, K.W., Prathumratana, L., Lee, A., Lee, K.Y., Kim, T.H., ... and Duong, B.D. 2011. Sustainable development in the mining sector and its evaluation using fuzzy AHP (Analytic Hierarchy Process) approach. *Geosystem Engineering* 14(1), pp. 43–50.

Pastakia, C.M. and Jensen, A. 1998. The rapid impact assessment matrix (RIAM) for EIA. *Environmental Impact Assessment Review* 18(5), pp. 461–482.

Pezeshkan, M. and Navid, H. 2020. An approach based on Fuzzy Best-Worst method for sustainable evaluation of mining industries. *Gospodarka Surowcami Mineralnymi – Mineral Resources Management* 36(2), pp. 41–70.

Pimentel et al. 2016 – Pimentel, B.S., Gonzalez, E.S. and Barbosa, G.N. 2016. Decision-support models for sustainable mining networks: Fundamentals and challenges. *Journal of Cleaner Production* 112, pp. 2145–2157.

Pishchulov et al. 2019 – Pishchulov, G., Trautrims, A., Chesney, T., Gold, S. and Schwab, L. 2019. The Voting Analytic Hierarchy Process revisited: A revised method with application to sustainable supplier selection. *International Journal of Production Economics* 211, pp. 166–179.

Rahmanpour, M. and Osanloo, M. 2017. A decision support system for determination of a sustainable pit limit. *Journal of cleaner production* 141, pp. 1249–1258.

Raj, A. and Srivastava, S.K. 2018. Sustainability performance assessment of an aircraft manufacturing firm. *Benchmarking: An International Journal* 25(5), pp. 1500–1527.

Rahmanpour, M. and Osanloo, M. 2017. A decision support system for determination of a sustainable pit limit. *Journal of cleaner production* 141, pp. 1249–1258.

Rajaram et al. 2005 – Rajaram, V., Dutta, S. and Parameswaran, K. 2005. *Sustainable mining practices: A global perspective*. London–New York: CRC Press.

Saeidi et al. 2017 – Saeidi, S., Mohammadzadeh, M., Salmanmahiny, A. and Mirkarimi, S.H. 2017. Performance evaluation of multiple methods for landscape aesthetic suitability mapping: a comparative study between multi-criteria evaluation, logistic regression and multi-layer perceptron neural network. *Land use policy* 67, pp. 1–12.

Salimi, N. and Rezaei, J. 2018. Evaluating firms' R&D performance using best worst method. *Evaluation and program planning* 66, pp. 147–155.

Santos et al. 2019 – Santos, B.M., Godoy, L.P. and Campos, L.M. 2019. Performance evaluation of green suppliers using entropy-TOPSIS-F. *Journal of cleaner production* 207, pp. 498–509.

Schlickmann et al. 2018 – Schlickmann, M., Dreyer, J., Spiazzi, F., Vieira, F., Nascimento, B., Nicoleite, E., Kanieski, M., Duarte, E., Schneider, C. and Aguiar, J. 2018. Impact assessment from coal mining area in southern Brazil. *Journal of Agricultural Science* 10(8), pp. 426–437.

Shields, D.J. 2005. USA and UN Perspectives on Indicators of Sustainability for the Mineral Extraction Industry. *A Review on Indicators of Sustainability for the Minerals Extraction Industries*.

Sitorus et al. 2018 – Sitorus, F., Cilliers, J.J. and Brito-Parada, P.R. 2018. Multi-criteria decision making for the choice problem in mining and mineral processing: Applications and trends. *Expert Systems with Applications*.

Stojčić et al. 2019 – Stojčić, M., Zavadskas, E.K., Pamučar, D., Stević, Ž. and Mardani, A. 2019. Application of MCDM methods in sustainability engineering: a literature review 2008–2018. *Symmetry* 11(3), 350.

Temple, S. 1992. Old issue, new urgency. *Wisconsin Environmental Dimension, Spring Issue* 1(1).

AN INTEGRATED APPROACH FOR PERFORMANCE EVALUATION OF MINING INDUSTRY: A CASE STUDY OF IRANIAN STEEL COMPLEX

Keywords

sustainable development, performance evaluation, mining industry, best-worst method, fuzzy inference system

Abstract

The continuous improvement in the industries and organizations hinges upon the evaluation of their performance. In fact, the performance evaluation assists organizations to identify their strengths and weaknesses and, accordingly, enhance their efficiency. As soon as the concept of sustainability was propounded in the engineering based industries, the performance evaluation got more importance due to the environmental issues and social concerns along with the economical aspects. Therefore, this paper is an attempt to propose an approach based on fuzzy best-worst method (BWM) and fuzzy inference system (FIS) in order to evaluate the performance of an Iranian steel complex in terms of sustainability concept. In the proposed approach, the weights of some selected criteria were determined by fuzzy BWM method and, then, the score of the under study industry was calculated in terms of economic, environmental, and social aspects. At the end, an FIS was developed to calculate the final score of the intended industry. In order to check the efficiency of the proposed approach, its performance was measured using expert knowledge as well as real data of a steel complex in Iran. A moderate to high performance has been achieved for the understudy case through conducting the proposed approach. It was suggested that the industry should focus on the criteria with both high weights and low evaluated scores (for example the environmental management technologies and knowledge criterion) to increase its performance evaluation score. The obtained results were indicative of the efficiency of the proposed approach.

ZINTEGROWANE PODEJŚCIE DO OCENY WYDAJNOŚCI PRZEMYSŁU WYDOBYWCZEGO: STUDIUM PRZYPADKU IRAŃSKIEGO KOMPLEKSU STALOWEGO

Słowa kluczowe

zrównoważony rozwój, ocena wydajności, górnictwo,
najlepsza–najgorsza metoda (*best-worst method*), rozmyty system wnioskowania

Streszczenie

Ciągłe doskonalenie branż i organizacji zależy od oceny ich wydajności. W rzeczywistości ocena wyników pomaga organizacjom zidentyfikować ich mocne i słabe strony, a co za tym idzie, zwiększyć ich efektywność. Jak tylko koncepcja zrównoważonego rozwoju została zaproponowana w branżach opartych na inżynierii, ocena wydajności nabrała większego znaczenia ze względu na kwestie środowiskowe i społeczne, a także aspekty ekonomiczne. Artykuł jest próbą zaproponowania podejścia opartego na rozmytej metodzie *best-worst* (BWM) i rozmytym systemie wnioskowania (FIS) w celu oceny wydajności irańskiego kompleksu stalowego pod kątem koncepcji zrównoważonego rozwoju. W proponowanym podejściu, wagi wybranych kryteriów wyznaczono metodą rozmytą BWM, a następnie obliczono punktację badanej branży pod względem ekonomicznym, środowiskowym i społecznym. Na koniec opracowano rozmyty system wnioskowania FIS, aby obliczyć końcowy wynik dla planowanej branży. Aby sprawdzić efektywność proponowanego podejścia, mierzono jego wydajność, wykorzystując wiedzę ekspercką oraz rzeczywiste dane dotyczące kompleksu stalowego w Iranie. W analizowanym przypadku, poprzez zastosowanie proponowanego podejścia osiągnięto wyniki od umiarkowanych do wysokich. Zasugerowano, że w celu zwiększenia oceny wyników, branża powinna skupić się na kryteriach zarówno o dużej wadze, jak i nisko ocenianych punktach (na przykład technologie zarządzania środowiskowego i kryterium wiedzy). Uzyskane wyniki świadczyły o skuteczności zaproponowanego podejścia.