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Sustainable Development Assessment in Underground Coal mining by Developing a Novel Index

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ABSTRACT

A novel index is presented in this paper to evaluate sustainable development in underground coal mining. Eleven parameters were chosen as impacting factors that define three aspects of sustainable development, including environmental, economic, and social. Fuzzy Delphi Analytical Hierarchy Process (FDAHP) was used to develop a new rating system in the form of a classification system. Subsequently, a sustainable development index (SDi) was defined as a simple summation of ratings for all parameters to classify the sustainability level of underground coal mining qualitatively. Applicability of the new index was examined through applying it to a case study, and the results were compared with a benchmark model. The results indicate that SDi possesses a higher performance in sustainable development evaluation in the actual case when compared to common models. This performance is because it is developed for underground coal mining, especially in a scientific manner that considers three aspects of sustainable development together.

Keywords : *Sustainable development; Underground coal mining; Fuzzy Delphi Analytical Hierarchy Process (FDAHP); Zemestan Yourt coal mine*

1. Introduction

Sustainable development (SD) is a general concept for all activities which was introduced in 1987 by World Commission on Environment and Development at United Nations named Our Common Future as: "sustainable development is a development that meets the needs of the present without compromising the ability of the future generations to meet their own needs" [1]. In the early 1990s, after the communities (e. g. the Rio Conference), SD was defined as the intersection of environment, economic, and social aspects [2].

Global population growth, high demand for resources, development, and economic growth have increased mining activities, which affect related environment, social, and economic sectors. Based on the concept of sustainable development, it requires special attention to resources policies due to the gradual depletion of reserves and future generations' concerns [3]. Up to now, many research studies have been conducted to address SD evaluation in mining industries. In this regard, the most comprehensive and common models in this field are Leopold matrix [4], Folchi technique [5], Rapid Impact Assessment Matrix (RIAM) [6] and Phillips [7, 8, 9].

Despite the development of clean and renewable energies, coal still holds a special place in the energy basket. Furthermore, it is an essential component in industrial processes such as steel and cement manufacturing. These issues play an important role in setting aims and priorities associated with the long-term development of coal industries and their ability to follow the rules of SD. Tajvidi Asr et al. (2019) reviewed the application of SD in the mining life cycle [10]. However, a literature review of SD in coal mining reveals that the most studied of coal mining consequences refer to the environmental study by ignoring other aspects of SD [11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22]. However, few comprehensive models for SD evaluation in underground coal mining include quantitative models and qualitative ones. In quantitative models, some equations have been developed to assess SD [3, 23, 24, 25] while, classification systems are proposed to SD evaluation in qualitative models [26, 27, 28, 29, 30, 31, 32]. There are many impacting factors that can be taken into account in SD evaluation in coal mining, as presented in Table 1.

Despite the conducted research to evaluate SD in underground coal mining, no studies have been carried out in the literature to take into account three aspects of SD by considering the most significant impacting factors in a scientific manner. Accordingly, and in light of these shortcomings, this paper aims to develop a novel index based upon a qualitative classification system by incorporating the most significant impacting factors. In this regard, a multi-criteria decision-making model under fuzzy environment was employed. The applicability of the proposed index has been examined by applying it to a real case study in Iran and then compared with the results of Philips model.

2. Methodology

In this work, to develop the new sustainable development index, the Fuzzy Delphi Analytical Hierarchy Process (FDAHP) method was utilized as a multi-criteria decision making (MCDM) approach. In order to study the applicability of the proposed index, the results of the real case study were compared to those of Philips model. Accordingly, in this section, the FDAHP method and Philips model are described.

2.1. Fuzzy Delphi Analytical Hierarchy Process (FDAHP) method

The FDAHP method is a common and efficient approach for

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decision-making, which was introduced by Kaufman and Gupta [36]. The Delphi technique is a strategy structured communication method by presenting information and evaluate group judgments to enable persons to revaluate their viewpoints. Besides, group decision-making is a very significant tool to speed up the consensus of different views from experienced judges [38].

Table 1: the most significant literature with their used impacting factors

Reference	Environmental								Economic					Social				
	AP	WP	SP	N	FP	EF	LD	EER	FP	MC	DNP	GDP	NPV	ELF	PRG	SK	HS	M
(Leopold et al., 1971) [4]	✓	✓	✓		✓				✓				✓				✓	
(Von Below, 1993) [32]									✓									
(Pastakia, 1998) [6]	✓	✓	✓	✓	✓	✓	✓	✓	✓					✓	✓	✓	✓	
(Folchi, 2003) [5]	✓	✓	✓	✓	✓		✓	✓	✓					✓	✓	✓	✓	
(Evans et al., 2007) [27]	✓	✓			✓					✓				✓			✓	✓
(Mirmohammadi et al., 2009) [35]	✓	✓	✓	✓	✓		✓	✓	✓				✓	✓	✓	✓	✓	
(Chikkatur et al., 2009) [28]	✓	✓	✓	✓	✓	✓	✓							✓	✓	✓	✓	
(Zhengfu et al., 2010)[11]	✓	✓	✓	✓	✓	✓												
(Si et al., 2010) [12]	✓	✓	✓	✓	✓	✓		✓	✓			✓	✓	✓				
(Cheng et al., 2011) [14]	✓	✓																
Sontamino and Drebenstedt, 2011) [13]	✓	✓	✓	✓	✓				✓	✓	✓					✓	✓	
(Phillips, 2010; 2012a; 2012b) [7, 8, 9]	✓	✓	✓	✓	✓	✓			✓							✓	✓	
(Cheng et al., 2011) [15]	✓	✓	✓			✓												
(Mukhopadhyay, 2013) [29]	✓	✓	✓		✓									✓	✓	✓	✓	
(Kowalska, 2014) [16]	✓	✓	✓	✓	✓	✓								✓	✓	✓	✓	
(Uddin at al., 2015) [30]	✓	✓	✓	✓	✓	✓						✓		✓	✓	✓	✓	
(Saini et al., 2016) [19]	✓	✓	✓	✓	✓			✓	✓	✓							✓	
(Ataei et al., 2016) [17]	✓	✓	✓	✓	✓	✓										✓	✓	
(Zhang et al., 2016) [31]	✓	✓	✓	✓	✓	✓			✓					✓	✓	✓	✓	
(Lei et al., 2016) [32]	✓	✓	✓	✓	✓	✓			✓					✓	✓	✓	✓	✓
(Yu et al., 2016) [18]	✓	✓	✓				✓	✓	✓					✓	✓	✓	✓	
(Saini et al., 2016) [21]	✓	✓	✓	✓	✓	✓		✓		✓	✓	✓		✓	✓	✓	✓	✓
(Kopacz at al., 2017) [23]	✓	✓	✓	✓	✓	✓	✓			✓				✓	✓	✓	✓	
(Bui et al., 2017) [3]	✓	✓	✓	✓	✓	✓	✓		✓	✓		✓	✓	✓	✓	✓	✓	
(Manowska at al., 2017) [36]										✓	✓	✓		✓	✓	✓		✓
(He at el., 2017) [20]	✓	✓	✓	✓	✓	✓		✓		✓	✓	✓		✓	✓	✓	✓	✓
(Norouzi Masir at al., 2018) [33]	✓	✓	✓	✓	✓	✓	✓		✓					✓	✓	✓	✓	✓
(Qi et al., 2019) [22]	✓	✓	✓	✓	✓	✓												✓
(Liu et al., 2020) [24]	✓	✓	✓	✓	✓				✓		✓					✓	✓	✓
(Hou et al,. 2020) [25]	✓	✓	✓	✓	✓				✓					✓		✓	✓	✓
(Tai et al., 2020) [26]	✓	✓	✓	✓	✓	✓			✓		✓			✓		✓	✓	✓

AP: Air Pollution; WP: Water Pollution; SP: Soil Pollution; N: Noise; FP: Forest Protection; EF: Energy and Fuel; LD: Land Disturbance; EER: Ecological Environment Recovery; FP: Fixed Price; MC: Mine Closure; DNP: Decline in National gross Product; GDP: Gross Domestic Production; NPV: Net Present Value; ELF: Employment of Local work Force; PRG: protecting the Rights of Future Generations; SK: Skills and Knowledge; HS: Health and Safety; M: Migration.

Due to the advantages of the FDAHP model in the determination of criteria weight, it is employed in this research by incorporating triangular fuzzy numbers (TFN). To that end, the following stages were conducted [39]:

(1) Calculation of triangular fuzzy numbers (TFNs): TFN ($\tilde{a}_{ij}$) computes by using Equation (1). In the current work, the TFNs (shown as Figure 1) indicating the pessimistic, moderate, and optimistic estimate is used to represent the opinions of experts for each activity time.

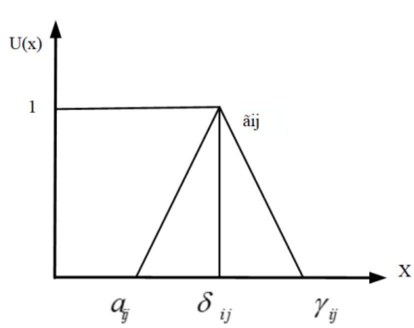

Figure1. Represent numbers of the fuzzy Delphi technique.

$$\tilde{a}_{ij} = \left(\alpha_{ij}, \delta_{ij}, \gamma_{ij}\right) \tag{1}$$

$$a_{ij} = Min\left(\beta_{ijk}\right), \quad k = 1, 2, \ldots, \mathrm{n} \tag{2}$$

$$\delta_{ij} = \left(\prod_{k=1}^{n} \beta_{ijk}\right)^{\frac{1}{n}}, \quad k = 1, 2, \ldots, \mathrm{n} \tag{3}$$

$$\gamma_{ij} = Max\left(\beta_{ijk}\right), \quad k = 1, 2, \ldots, \mathrm{n} \tag{4}$$

where $\alpha_{ij} \le \delta_{ij} \ge \gamma_{ij}$, $\alpha_{ij}, \delta_{ij}, \gamma_{ij} \in \left[\frac{1}{9}, 1\right] \cup [1, 9]$ which are calculated using Eqs. (2)-(4). α_{ij} and γ_{ij} show the lower and the upper bound, respectively. B_{ijk} shows the relative intensity of importance of expert k between activities i and j. n is the number of experts consisting of a group.

(2) Obtaining a fuzzy positive reciprocal matrix: the fuzzy positive reciprocal matrix, $\tilde{A}$ is achieved as follow:

$$\tilde{A} = [\tilde{a}_{ij}], \quad \tilde{a}_{ij} \times \tilde{a}_{ij} \approx 1, \quad \forall i, \quad j = 1, 2, \ldots n \tag{5}$$

(3) Calculating the relative fuzzy weights: the relative fuzzy weights of the assessment parameters are estimated as follow:

$$\tilde{Z}_i = [\tilde{a}_{ij} \otimes \ldots \otimes \tilde{a}_{in}]^{1/n} \tag{6}$$

$$\tilde{W}_i = \tilde{Z}_i \otimes (\tilde{Z}_i \oplus \ldots \oplus \tilde{Z}_n)^{-1} \tag{7}$$

Where $\tilde{a}_1 \otimes \tilde{a}_2 = (\alpha_1 \times \alpha_2, \delta_1 \times \delta_2, \gamma_1 \times \gamma_2)$. The symbol $\otimes$ shows the multiplication of fuzzy numbers, and the symbol $\oplus$ shows the addition of fuzzy numbers. $\tilde{W}_i$ is a row vector in consist of a fuzzy weight of the ith factor $(\tilde{W}_i = (\omega_1, \omega_2, \ldots, \omega_n), i = 1, 2, \ldots, n)$ which is indicated a fuzzy weight of the ith criterion.

(4) Defuzzification weight of factors: in order to defuzzify weights of parameters, geometric average of the fuzzy number is used (Eq. (8)):

$$W_i = (\prod_{i=1}^{3} w_{ij})^{\frac{1}{3}} \tag{8}$$

2.2. Philips model

Phillips model is a mathematical model for sustainability assessment that indicates the SD level quantitatively. This method defines factors and constraints of the key aspects as well as the conditions under which sustainability or unsustainability can happen [8, 9]. The steps for using this model are as follow:

1) Implementing Environmental Impact Assessment (EIA)
2) Evaluating all project options and determination of the environmental and human aspects and their scores:
- Environmental aspects (*E*) include Air quality (A_1), Quietness (A_2), Ecology (B_1), Surface water (H_1), Underground water (H_2), Area usage (L_1), Surface constructions (L_2), Underground constructions (L_3), Area landscape (L_4), Soil of the area (L_5).
- Human components (H_{NI}) include Human health and immunity (H_{NI1}), Social subjects (H_{NI2}), Economic subjects (H_{NI3}).

It should be noted that in Philips method, the maximum score is 100 for E and H_{NI} (Table 2).

Table 2. Maximum Scores of E and HNI aspects

E and HNI Components	Scores
A max	200
B max	100
H max	200
L max	500
E max	1000
HNI max	300

3) Calculating E and HNI1 for the project options as follows:

$$E = \frac{(\sum A_{max} - (A_1 + A_2)) + (\sum B_{max} - (B_1))}{(\sum A_{max} + \sum B_{max} + \sum H_{max} + \sum L_{max})} + \frac{(\sum H_{max} - (H_1 + H_2)) + (\sum L_{max} - (L_1 + L_2))}{(\sum A_{max} + \sum B_{max} + \sum H_{max} + \sum L_{max})} \tag{9}$$

$$H_{NI} = \frac{[(H_{NI1} + H_{NI2}) + (H_{NI3max} - H_{NI3})]}{\sum H_{NI3max}} \tag{10}$$

4) Determining whether the project is sustainable or not:
- If the value of E is higher than the value of H_{NI}, then the project is sustainable otherwise, it is unsustainable.
- Calculating the *S* value by the following equation for the project in the event of sustainability.

$$S = E - H_{NI} \tag{11}$$

- Determining the level and nature of sustainability with the use of Table 3.

Table 3. S value and level

Sustainability	Range
Very Strong	0.751 – 1.000
Strong	0.501 – 0.750
Weak	0.251 – 0.500
Very Weak	0.001 – 0.250

3. Presenting the sustainable development index (SDi)

In order to present a new sustainable development index (SDi), first, the impacting factors in each aspect were selected and defined. After that, the FDAHP was applied to weight them, and then a classification system was introduced. In the following, each step will be described.

3.1. Impacting factors

Many impacting factors can be taken into account in SD evaluation in coal mining, as presented in Table 1. In this regard, by taking into account the frequency of the use in the previous work (Table 1), recommendations of the experts, and analysis, the factors related to SD in underground coal mining were classified (Figure 2) based on the following rules:

(a) The number of impacting factors must be low.
(b) Using equivalent impacting factors must be avoided.
(c) Measuring the parameters must be easy.

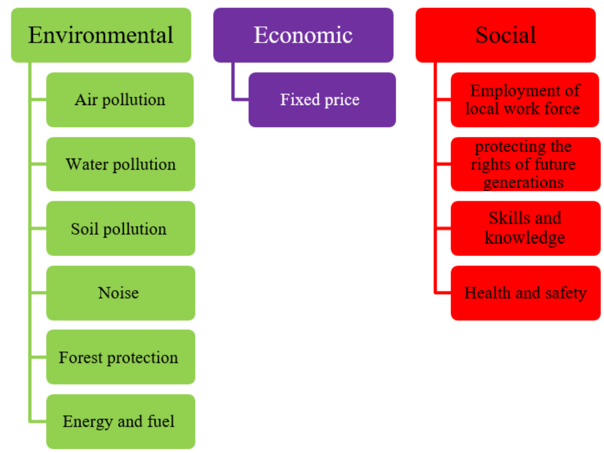

Figure 2. Factors for sustainable development

3. 1. 1 Environmental aspect

- In this category, environmental pollution (i.e., air, water, and soil), noise, changes in forest and consumption of energy and fuel were considered:
- Air pollution arising from underground coal mining is mostly due to CH4, which is a powerful greenhouse gas, discharged through the ventilation systems.
- Water pollution in underground coal mines is caused by changing in water PH, increasing heavy metals in water, and mixing waste with surface waters as well as underground water.
- Soil pollution is frequently because of heavy elements, pH change, cementation, and salt formation.
- Noise is produced by blasting operation and mining equipment such as compressors, mining machines, fans, pumps, among others.
- Change in forest view is due to two main reasons, including the use of wood for support goals in stopes (consumption of 40kg wood per a ton coal) and land leveling to construct infrastructures.
- Energy and fuel are indicative of the consumption of water, electricity, gasoline, and etc. An increase in energy consumption leads to increasing the harmful consequences applied to the environment from different viewpoints.

3. 1. 2 Economic aspect

Fixed price is one of the most important economic aspects used in most studies. It represents many economic factors such as capital expenditures, operating costs, the share of domestic coal production, rate of return, and net present value.

3. 1. 3 Social aspect

The social aspect of SD in underground mining was comprised of 4 factors, as follow:

- The employment of local workforces is determined by the number of people who work in the mine. Culture and community in every town are in direct relation to resident people and employment structure in that town.
- By developing coal mining skills and mining services in the region, the skills and knowledge of miners can be increased.
- Rich coal mines in different parts of the world have positive and negative effects on culture and local satisfaction. This influence

causes effects on the social life of people. Also, protecting the rights of future generations can be considered representative of being strategic in energy and local satisfaction.

- Coal mines are high-risk mines in which workers are always exposed to various health and safety issues.

3. 2. Presenting the classification system

In order to determine the weight of impacting factors using the FDAHP, some questionnaires were collected from the decision group, and their pair-wise comparisons were analyzed. Accordingly, after defuzzify obtained weights, the deterministic weight of impacting factors were calculated, as shown in Figure 3.

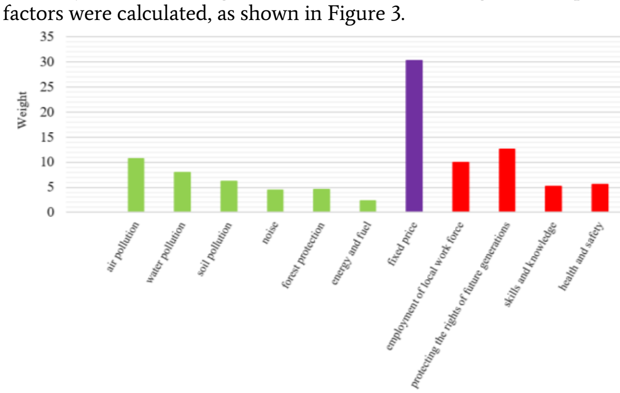

Figure 3. Importance levels of the sustainability impacting factors in ultimate

In order to establish the classification system, various levels of each impacting factor were defined based on the national and international standards, guidelines, and literature. Afterward, a portion of the ultimate weight of the parameter was assigned to each level. For this purpose, five classes were defined in which the ideal class (the best value for sustainability) gives 100% of weight, while 10% of the ultimate weight was assigned to the worst one (Tables 4-6). Therefore, the sustainable development index (SDi) was defined as the summation of parameter scores. In this regard, higher SDi indicates higher sustainability, whereas lower values are associated with the worse situation of sustainable development. Using the SDi computational procedure, the minimum and maximum possible ratings of sustainability are 10 and 100, respectively. The mine state with respect to sustainable development was classified into five groups, depending on the value of SDi, as listed in Table 7.

4. Application of the proposed index

The application of the proposed index was examined in a real case in Iran. For this aim, Zemestan Yourt underground coal mine was considered as a case study. This mine is located in the Gorgan province, about 14 km from the Azadshahr city (Figure 4). The mining area is mountainous and mostly rainy in all seasons. Therefore, it is covered by vegetation with forest shrubs. The reserve value of the mine is about 1,265,000 tons, with an annual production of 3,457 tons [40].

Table 4: Rating table of environmental impacting factors.

impacting factor	Class				
Air pollution (mgr/m3)	1<	1-5	5-10	10-20	<20
Score	10.76	7.532	5.38	2.69	1.076
Water pollution (mg/l)	1<	1-3	3-5	5-7	<7
Score	7.96	5.572	3.98	1.99	0.796
Soil pollution (mg/kg)	10<	10-50	50-100	100-150	<150
Score	6.24	4.368	3.12	1.56	0.624
Noise dB (A)	60<	60-75	75-85	85-95	<150
Score	4.49	3.143	2.245	1.1225	0.449
Forest protection	High risk of erosion and vegetation growth is unlikely	Critical point of erosion and poor probability of success in rebuilding vegetation	Mild risk of erosion and the average chance of success in rebuilding vegetation.	Mild risk of erosion and high probability of success in rebuilding vegetation.	Low erosion risk and very high probability of rebuilding vegetation
Score	4.6	3.22	2.3	1.15	0.46
Energy and fuel (kWh/(t·km))	0.6<	0.6- 2.4	2.4-4.2	4.2-6	<6
Score	2.29	1.603	1.145	0.5725	0.229

Table 5: Rating table of economic impacting factors

impacting factor	Class				
Fixed price (Million Rial per ton)	200000<	200000- 400000	400000-600000	600000-800000	<800000
Score	30.29	21.203	15.145	7.573	3.029

Table 6: Rating table of social impacting factors

impacting factor	Class				
Employment of local work force (%)	12<	12-20	20-28	28-36	<36
Score	0.994	2.458	4.97	6.958	9.94
protecting the rights of future generations	-full maintaining the national wealth of the country - Reducing unemployment in the community Achieving sustainable development goals	- Preserving national wealth - Reducing unemployment in the community	- Maintain relative national wealth - The relative decline in unemployment in the community	- Critical risk of maintaining national wealth - Increased unemployment in the community	- Failure to maintain the country's national wealth - The critical risk of unemployment in society - Not achieving sustainable development goals
Score	12.56	8.792	6.28	3.14	1.256
Skills and knowledge	- employees less need to attend training courses	- employees medium need to attend training courses	- employees more need to attend training	- employees more need to attend training courses	- employees maximum need to attend training

	- The least positive and negative impact on the culture of the region		courses - Positive and negative relative effects in regional culture	- Risk of Positive and Negative Impact on the culture of the region	courses - The most positive and negative influences in the culture of the region
Score	0.515	1.2875	2.575	3.605	5.15
Health and safety	- Protect the health of miners - Maintaining the economy of the country	- Protect the health of miners - Maintaining relative economy of the country	- Maintain average health of miners - Maintaining relative economy of the country	- Increasing the health risk of mining personnel - Increased damage to the economy of the country	- Failure to maintain the health of miners - Failure to maintain the economy of the country
Score	5.15	3.913	2.795	1.3975	0.559

Table 7: Classification of *SDi*

SDi	100-80	80-60	60-40	40- 20	20-10
Sustainability	excellent	good	fair	poor	very poor

Figure4. The location of the Zemestan Yourt coal mines in Iran.

Table 8 shows the SDi calculation procedure for the case study in which the value or state of each parameter and their assigned scores are listed based on Tables 4-6. In this regard, the SDi in the Zemestan Yourt underground coal mine is 39.029, placing it in a poor level of sustainability.

E and H_{NI} are computed using Eqs. (9) and (10), as follow:

$E = 0.85517$; $H_{NI} = 0.3482$

As can be seen, E is greater than H_{NI} thus, the project is evaluated as sustainable.

Finally, the S value was computed using Eq. (11) that is 0.507. Based on Table 8, it can be concluded that the sustainability of the Zemestan Yourt coal mine is in the strong class of sustainability.

5. Discussion

The main goal of this study was to develop an index for evaluating the sustainable development level in underground coal mines. Accordingly, the results of sustainable development evaluation in a real case using a proposed model were compared with those of the Philips model.

The findings of this study indicate a meaningful difference in the classifying sustainability level of the Zemestan Yourt underground coal mine using the two models. SDi evaluates the case study in poor condition while the Philips method classifies it in the strong level of sustainability.

Table 9 shows the results of EIA using the Philips model for the case study.

Table 8: Calculation of SDi for the Zemestan Yourt mine

Aspects	Impacting factor	Amount or status	*Score*
Environmental	Air pollution (gr/m^3)	3.32	7.532
	Water pollution (mg/l)	2.00	5.572
	Soil pollution (mg/kg)	150	1.56
	Noise dB (A)	75	2.245
	Forest protection	Low to moderate	2.3
	Energy and fuel (kWh/(t·km))	2.3	1.603
Economic	Fixed price (Million rials per ton)	810000	3.029
Social	Employment of local work force (%)	25	4.97
	protecting the rights of future generations	Low to moderate	6.28
	skills and knowledge	Low to moderate	1.398
	health and safety	moderate	2.575
SDi			$SD_i = \sum_{i=1}^{11} rate_{SD} = 39.029$

Table 9. Ultimate scoring for every environmental aspect in Zemestan Yourt coal mine

score	environmental aspect
28.03	Air quality
10.6	Quietness
11.3	Ecology
13.5	Surface water
13.44	Underground water
7.02	Area usage
15.08	Surface constructions
16.77	Underground constructions
14.02	Area landscape
15.07	Soil of the area
20.45	Human health and immunity
19.35	Social subjects
35.34	Economic subjects

Since this mine exploited using the un-mechanized mining method, the safety and health of workers are lower than the mechanized method, while the consumption of wood, fuel, and air pollution due to the diesel machines is higher than the mechanized one. Despite the efforts made by the mine managers, some factors cannot be controlled in the mine, such as the mountainous environment and continuous rains, which cause serious environmental problems. In addition, some social-political factors, such as the low price of coal or labor salary, reduce the economic and social standards. Also, the sanctions limit access to modern technologies and equipment as well as supplying spare parts. These limitations reduce the performance of the mine and impose further safety and health risks as well as environmental issues. In this regard, field observations and managers' opinions show that the mine is at a weak to moderate (ideally) level of sustainability. Therefore, it is concluded that the results of the proposed model are in accordance with the real situation of the mine.

Accordingly, the findings indicate that the proposed model possesses a higher performance in the prediction and analysis of sustainability in underground coal mines in actual cases when compared to the Philips model. This higher performance is because the proposed model has been developed specifically for underground coal mines, with given environmental, economic, and social situations in the definition of impacting factors. Besides, determining the weights of the impacting factors was conducted using a scientific approach by incorporating the judgment and opinion of several experts. Also, simultaneous consideration of three aspects of sustainable development in the proposed model provides more effective insight into sustainable development, as carried out in the proposed model.

6. Conclusions

In this paper, a new model was presented by introducing a sustainable development index (*SDi*) to evaluate sustainable development in underground coal mines. For this purpose, a classification system was developed using the FDAHP method. The following main conclusions could be made from this work:

- It was concluded that the environmental factor is the most important aspect of evaluating sustainable development in underground coal mining (with a weight of 36.47%). After that, social factors had higher importance (33.24%) in comparison to economic ones (30.29%).
- The proposed index showed that Zemestan Yourt, an underground coal mine in Iran, is in a poor sustainability level. However, the Philips method evaluated this mine to be on a strong sustainability level.
- By comparing the obtained results with the real situation, SDi was found to be superior in comparison to the Philips method in evaluating sustainable development in underground coal mining.

In SDi, all the aspects of sustainable development simultaneously were considered, and the weighting and rating process was carried out via a scientific procedure. Thus, SDi provides more reliable results for the evaluation of sustainable development in underground coal mines.

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