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Professional paper

A fuzzy DEMATEL based sustainable development index (FDSDI) in open pit mining – a case study

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Abstract
As an economic activity, mining can have positive and negative effects for the community. These negative impacts along with some of the social, economic, and environmental impacts of mining actions threaten the achievement of sustainable development (SD) goals. Therefore, an impact evaluation of SD indexes is significant for protecting mining actions in line with the objectives of SD. For that reason, a system classification was proposed with the use of the fuzzy decision-making trial and evaluation laboratory (fuzzy DEMATEL) technique to study and analyse eleven impacting factor interrelationships in open pit mines. Since this technique is based upon the opinion of experts, the fuzzy coding technique was used. In this manner, the weight of the impacting factors and their related ratings were chosen to develop a new classification system. Based on the proposed rating system, FDSDI was introduced to describe system-levels qualitatively and quantitatively. The application of FDSDI was investigated in a bauxite mine as a case study. The results show that FDSDI is an easy and effective tool to evaluate sustainability in bauxite mining. Generally, the conducted technique presents a systematic approach for holistic analysis of the impacting factors of SD in open pit mines.

Keywords:
Fuzzy decision-making trial and evaluation laboratory, classification system, zone, Jahjarm bauxite mine

1. Introduction

Nowadays, due to increases in the world population and the growing demand for an increase in the production rate of minerals, industries are necessary. In the world, production is important in open-pit mines. More than 90 percent of Iran's mines have been mined by using open pit mining techniques, which have a considerable share in creating jobs, supplying essential raw materials, income distribution, expanding social infrastructures and the economics of the country (**Moradi, and Osanloo, 2015; Norouzi Masir et al., 2018**). Regardless of all these benefits, mining activities lead to the production of many hazards for the health and safety of mineworkers, damage to the natural environment (e.g. water, air, and soil pollution, land disruption, subsidence), and various social problems (**Marker et al., 2005; Owen and Kemp, 2017**). In this regard, if the increase in the production rate is not monitored, future generations will have problems. In this regard, sustainable development (SD) has been widely used to deal with these issues and challenges. Understanding sustainable development practices can be a useful tool to help solve these issues, and thus, using SD has become an important topic in international business studies (**Campbell et al., 2012; Egri and Ralston, 2008; Vivoda and Kemp, 2019).** Hence, in this paper, SD assessment has been used, because it pays attention to SD in mining activities, reduces environmental problems, and has positive social and economic effects (**Norouzi Masir et al., 2018; Buchanan and Marques, 2018; Dashwood, 2012**).

The concept of SD is now widely spread. There are several definitions and schools of thought of SD available in literature. One such publication on SD was released by the World Commission on Environment and Development at the United Nations in 1987 in a report entitled "Our Common Future" as it "meets the needs of the present without compromising the ability of the future generations to meet their own needs" (**Brundtland Report, 1987**). This issue was discussed in the United Nations Conference on development and the environment in **Rio de Janeiro** in **1992**, causing business organizations universally to begin to adopt SD policies (**Gladwin et al., 1995; Stoughton and Ludema, 2012**). Generally, this report shows that developing countries have presented models, taken innovations and are more committed to achieving the goals of SD than their counterparts in the developed world. Basically, SD is a practical requirement and needs universal support to ensure that economic actions are realized in an advanced society, and yet still leave a well-preserved environment (**Sachs and Reid, 2006; DES, 2013**). The implementa-

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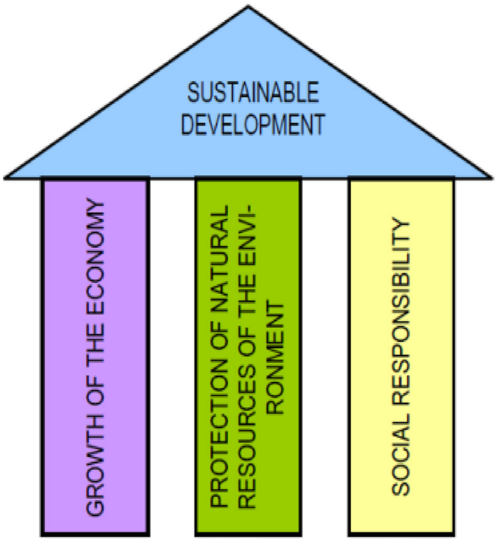

Figure 1: Key aspects of SD (**Dubinsky, 2013**)

tion of SD means a combination of activities in the following three key parts (see **Figure 1**) (**Dubinsky, 2013**):

Technical and economic, ensuring economic growth,

Environmental, guaranteeing the protection of natural resources and the natural environment,

Social, paying attention to employment and community development.

Since the early **1990s**, SD studies in the mining industry have been presented and in **1992**, the concept of SD gained interest among miners from the United Nation's Earth Summit Conference in Rio de Janeiro, Brazil (**Osanloo and Rahmanpour, 2017**). Since then, different studies of SD in the mining industry have been presented (**Allen, 1991; Auty and Warhust, 1993; VonBelow, 1993; Mikesell, 1994; Allan 1995; Tilton, 1996; Learmont, 1997; Carbon, 1997; James, 1999; Hilson and Murck 2000; Hilson and Basu, 2003; Rajaram et al.,**

Table 1: Summary aspects of SD research in open pit mining

Reference	Study type	Study origin	Case	Major objective/outcome
Gardner and Bell, (2007)	Survey and case study	Australia	Alcoa mine	Discussed Bauxite mining restoration social, political, historical, and environmental contexts.
Rashidinejad et al. (2008)	Survey	General		offered an environmental oriented model for optimum cut-off grades
Monjezi et al. (2009)	Survey and case study	Iran	Mouteh gold mine, Gol-eGohar mine, Chogart iron mine, and Sarcheshmeh copper mine	Reviewed Folchi method for the EIA of open-pit mining in Iran.
Pavloudakis et al. (2009)	Survey and case study	Northern Greece	Amynteon lignite surface mine	Developed a spatial decision support system for the optimal environmental reclamation of open-pit coal mines.
Philips, (2012)	Survey and case study	India	Andhra Pradesh mine	Applied a mathematical model of sustainability to the environmental impact assessment (EIA) of a proposed bauxite mining project.
Temper and Martinez-Alier, (2013)	Survey and case study	India	Odisha and the Lanjigarh refinery	Described an environmental and institutional history for determining Net Present Value (NPV).
Badiozamani and Askari-Nasab, (2014)	Survey and case study	-	Real dataset of oil sands mine	Assessed a new mixed integer linear programming model (MILP) model to maximize the NPV by considering the reclamation costs in its aims function.
Lad and Samant, (2015)	Survey and case study	India	Udgiri, Dist-Kolhapur, Maharashtra State	Described the impact of bauxite mining on soil pollution.
Narrei and Osanloo. (2015)	Survey and case study	Iran	Gol-Gohar iron mine	Provided a model for determining cut off grades by considering possible incomes from reclamation
Leblanc et al. (2015)	Survey and case study	Australia	Cape York Peninsula	Proposed a study on the hydrology of the bauxite oases.
Amirshenava and Osanloo (2018)	Survey and case study	Iran	Choghart iron ore mine	Presented a general procedure for mine closure risk management.
Srikanth and Nathan (2018)	Review and case study	India	Surface coal mines	Studied the surface coal mine closure policies

2005; Eggert, 2006; Horowitz, 2006). This research shows how mining and minerals can contribute to SD.

As mentioned before, nowadays, most of the minerals are produced by open pit mining methods and these operations affect the aspects of SD (environmental, social and economic). A summary of environmental, environmental-economic and environmental-social studies aspects of SD research in open pit mining is presented in **Table 1**.

As can be seen in **Table 1**, a number of studies didn't consider all aspects of SD in open pit mines (environmental, economic and social) together while these aspects are related to each other. In the following segment, recent research in this context is reviewed.

In **2004**, **Ramirez-Rodriguezm and Rozgonyi**, estimated the cut-off grade using Lane's algorithm, one of the most popular algorithms for determination of the optimum cut-off grade, by applying the cost of reconstruction in the design and planning of open pit mines. The results indicated that the integration of the SD requirements in mining profitability and optimum cut-off grades is very necessary. **Rahimi and Ghasemzadeh** in **2015** offered a new algorithm for the determination of the optimum cut-off grades by considering SD aspects. This research showed that applying hydrometallurgical techniques for low grade copper ores instead of pyrometallurgical ones not only improves the NPV of copper mines but also reduces the adverse environmental effects and creates sustainable results from mining operations. **Moradi and Osanloo,** in **2015**, studied prioritizing SD aspects affecting open pit mine design using the Preference Voting System (PVS) based on a model of DEA. The results showed that this research can be offered unique standards in the SD impacting factors ultimate pit limit (UPL) design in different metal mines, and the shares of the environmental, economic and social aspects are 26, 38 and 36%, respectively. **Adibi and Ataee-pour**, in **2015,** developed a model based upon SD aspects to consider the economic and social benefits and decrease the negative environmental impacts of an open pit mine during UPL design and before exploitation. The presented model was explained with a simple 2D example and used in the Jalalabad iron mine as a case study. The results indicated that when the mining investor ignores a little of the mining profit, improvement in all aspects of SD in mining is possible. In the same study, **Adibi et al**. in **2015**, reused the mentioned model in a copper mine for solving the "UPL selection based upon SD aspects" problem utilizing the TOPSIS technique. The paper analysis indicated that the UPL selected by the proposed technique had higher social and economic ratings compared to the traditional UPL. It also contained greater ore and lower profit than the traditional UPL. **Rahmanpour and Osanloo** in **2017**, in a study project offered two mining plans in the Sungun copper mine with the title "mine design selection considering SD", one based upon maximizing the maximum net present value of the mine and the other for maximizing the lifetime of the mine, utilizing the Folchi technique to determine which plan had more validity based on the aspects of SD.

Although this research has provided a significant role in the assessment of SD in open pit mining, the greatest shortcoming of these studies is developing a comprehensive evaluation related to a classification system of SD issues in open pit mining. In addition, no scientific or systematic approach by using fuzzy DEMATEL was applied to quantitatively evaluate the weighting of impacting parameters in open pit mining. Accordingly, this paper presents a generic procedure for qualitatively and quantitatively evaluating impacting factors in open pit mining operations in a SD index. Finally, this index was assessed in a real case.

2. Method

2.1. Fuzzy DEMATEL method

Fuzzy DEMATEL is a common and efficient method for decision making. The fuzzy DEMATEL technique is a strategy for constructing an efficient group communication method. It provides feedback on contributions of knowledge and evaluation of group experts to enable individuals to assess their viewpoints. Actually, an individual's opinion with preferences in decision-making, generally, is often uncertain and difficult to calculate by accurate numerical values, thus the use of fuzzy logic is a necessity. That's why, to deal with the uncertainty of individual evaluations, the preferences of experts are increased to fuzzy numbers by accepting the fuzzy linguistic scale. (**Fontela and Gabus 1972, 1974, 1976**).

In this article, by using triangular fuzzy numbers (TFN) in the fuzzy DEMATEL method, the relative fuzzy weights of the decision factors are estimated utilizing the five stages mentioned below and the relative fuzzy weights are accumulated to obtain scores for the impacting factors (**Mohammadi et al., 2018**):

Stage 1: Obtaining the initial and average direct relation matrix. For this aim, judgments show the direct influence that factors i judgments on the criterion j utilizing a TFN. The TFN corresponding to every one of the linguistic scales is shown in **Table 2.**

If there are h experts and n factors, so each expert makes the $n \times n$ non- negative matrix $\tilde{Z}^k$, with $1 \leq k \leq h$.

Table 2: Fuzzy linguistic comparison chart

Linguistic terms	Linguistic value
Very High Influence (VH)	(0.75, 1.0, 1.0)
High Influence (H)	(0.5, 0.75, 1.0)
Low Influence (L)	(0.25, 0.5, 0.75)
Very Low Influence (VL)	(0, 0.25, 0.5)
No Influence (NO)	(0, 0, 0.25)

Hence, $\tilde{Z}^1$, $\tilde{Z}^2$, …, $\tilde{Z}^h$ are the resulting matrices for each of the h experts. The elements of $\tilde{Z}^k$ are $\tilde{z}_{ij} = (l_{ij}, m_{ij}, u_{ij})$ which in the first, second, and third terms represent the lower, middle, and upper bounds of TFN that shows the direct influence of factor i on factor j based on the opinion of k^{th} expert. $\tilde{A}$ is illustrated as **Equation 1**:

$$\tilde{A} = \frac{(\tilde{Z}^1 \oplus \tilde{Z}^2 \oplus ... \oplus \tilde{Z}^h)}{h} \quad (1)$$

Where:

$\tilde{Z}^k$ - Direct relation fuzzy matrix,

$\tilde{A}$ - Average direct relation matrix,

h - Expert's value.

Stage 2: Establishing the normalized direct relation matrix. The normalized direct relation matrix $\tilde{X}$ is achieved via normalizing the matrix $\tilde{A}$ presented as **Equation 2** and **3**:

$$\tilde{X} = \frac{\tilde{A}}{r} \quad (2)$$

$$r = \max[\max_{1\le i\le n} \sum\nolimits_{j=1}^{n} u_{ij}, \max_{1\le j\le n} \sum\nolimits_{i=1}^{n} u_{ij}],$$

$$i, j = 1, 2, ..., n. \quad (3)$$

Let $\tilde{x}_{ij} = (l'_{ij}, m'_{ij}, u'_{ij})$ be the factors of $\tilde{X}$ and describes three crisp matrices, whose factors are extracted from $\tilde{X}$ as follows:

$$X_l = \begin{bmatrix} 0 & l'_{12} & \cdots & l'_{1n} \\ l'_{21} & 0 & \cdots & l'_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ l'_{n1} & l'_{n2} & \cdots & 0 \end{bmatrix} \quad X_m = \begin{bmatrix} 0 & m'_{12} & \cdots & m'_{1n} \\ m'_{21} & 0 & \cdots & m'_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ m'_{n1} & m'_{n2} & \cdots & 0 \end{bmatrix}$$

$$X_u = \begin{bmatrix} 0 & u'_{12} & \cdots & u'_{1n} \\ u'_{21} & 0 & \cdots & u'_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ u'_{n1} & u'_{n2} & \cdots & 0 \end{bmatrix}$$

Where:

l'_{ij} - lower bounds of TFN value,

m'_{ij} - middle bounds of TFN value,

u'_{ij} - upper bounds of TFN value.

Stage 3: Estimating the total relation matrix. The total relation matrix $\tilde{T}$ is estimated utilizing following formulas (see **Equation 4 and 5**):

$$\tilde{T} = \tilde{X}(\mathrm{I} - \tilde{X})^{-1} \quad (4)$$

Where:

I - the unit matrix.

Let

$$\tilde{T} = \begin{bmatrix} \tilde{t}_{11} & \tilde{t}_{12} & \cdots & \tilde{t}_{1n} \\ \tilde{t}_{21} & \tilde{t}_{22} & \cdots & \tilde{t}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{t}_{n1} & \tilde{t}_{n2} & \cdots & \tilde{t}_{nn} \end{bmatrix} \quad (5)$$

Where its elements are $\tilde{t}_{ij} = (l''_{ij}, m''_{ij}, u''_{ij})$. With regards to the crisp case, the crisp factors of total relation matrices estimated as:

$$\mathrm{T}_l = [l''_{ij}] = X_l(\mathrm{I} - X_l)^{-1}; \ \mathrm{T}_m = [m''_{ij}] = X_m(\mathrm{I} - X_m)^{-1};$$

$$\mathrm{T}_u = [u''_{ij}] = X_u(\mathrm{I} - X_u)^{-1}$$

Where:

l''_{ij} - lower bounds of TFN value,

m''_{ij} - middle bounds of TFN value,

u''_{ij} - upper bounds of TFN value.

Stage 4: Set up the causal diagram. After obtaining matrix $\tilde{T}$, sum of rows (r) and sum of columns (c) of the total relation matrix based on the formula are estimated in **Equations 6** and **7**:

$$[r_{ij}]_{n\times 1} = \left(\sum_{j=1}^{n} l_{ij}, \sum_{j=1}^{n} m_{ij}, \sum_{j=1}^{n} u_{ij}\right), \qquad i, j = 1, 2, \ldots, n \quad (6)$$

$$[c_{ij}]_{1\times n} = \left(\sum_{i=1}^{n} l_{ij}, \sum_{i=1}^{n} m_{ij}, \sum_{i=1}^{n} u_{ij}\right), \qquad i, j = 1, 2, \ldots, n \quad (7)$$

Where:

r - the total exert influence on the others,

c - the total influence received from the others,

l_{ij} - lower bounds of TFN value,

m_{ij} - middle bounds of TFN value,

u_{ij} - upper bounds of TFN value.

Stage 5: Computing the weight of criterion. At this stage, the weight of every factor ($\tilde{W}i$) is specified as **Equation 8**:

$$\tilde{w}_i = \left(\frac{l_{r_i} + l_{c_i}}{\sum_{i=1}^{n} l_{r_i} + \sum_{i=1}^{n} l_{c_i}}, \frac{m_{r_i} + m_{c_i}}{\sum_{i=1}^{n} m_{r_i} + \sum_{i=1}^{n} m_{c_i}}, \frac{u_{r_i} + u_{c_i}}{\sum_{i=1}^{n} u_{r_i} + \sum_{i=1}^{n} u_{c_i}} \right) \quad (8)$$

At this stage, the results of fuzzy DEMATEL is a fuzzy number. Thus, the defuzzification of fuzzy numbers is a compulsory issue. For this aim, the Best Non-fuzzy Performance (BNP) technique was applied to defuzzification the values of r, c, and $\tilde{W}i$ which is described based on **Equation 9**:

$$BNP = l + \frac{(\mathrm{u} - \mathrm{l}) + (\mathrm{m} - \mathrm{l})}{3} \quad (9)$$

Where:

l - lower bounds of TFN value,

m - middle bounds of TFN value,

u - upper bounds of TFN value.

2.2. Development of a new classification system

In order to present a classification system for evaluating SD, it is necessary to identify the most significant parameters that govern SD performance. For this purpose, the following rules were taken into account:

Figure 2: Impacting factors involved for a SD

- Utilizing the minimum number of parameters,
- The non-parallel and non-overlapping parameters,
- The ease of measurement of parameters, and
- The definition of ability in a wide range of bauxite measure environs (parameters generality).

Based on the above rules, for presenting a classification system of SD, 11 impacting factors were selected by considering the literature review, experts' opinions, and our own analysis as illustrated in **Figure 2.**

By analysing the impacting factors on the SD, the direct relation matrix was established as displayed in **Figure 3**.

$$X = \begin{bmatrix} 0 & x_{12} & \cdots & x_{1n} \\ x_{21} & 0 & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & 0 \end{bmatrix}$$

Figure 3: Direct relation matrix

In the direct relation, the matrix was evaluated using the fuzzy DEMATEL method. To establish the direct relation matrix, questionnaires were distributed among 20 academics and industrial experts and their opinions and judgments were collected, where 15 questionnaires were

Table 3: The crisp matrix of the fuzzy total relation matrix

T	C_{11}			C_{12}			C_{13}			C_{14}			C_{15}			C_{16}			C_{21}			C_{31}			C_{32}			C_{33}			C_{34}		
C_{11}	0.00	0.00	0.04	0.03	0.05	0.08	0.02	0.04	0.07	0.01	0.02	0.05	0.03	0.05	0.08	0.01	0.03	0.06	0.03	0.05	0.08	0.03	0.02	0.04	0.04	0.06	0.03	0.01	0.01	0.04	0.05	0.03	0.06
C_{12}	0.01	0.01	0.06	0.01	0.01	0.04	0.03	0.05	0.07	0.00	0.01	0.04	0.03	0.05	0.08	0.01	0.03	0.06	0.04	0.06	0.09	0.03	0.04	0.07	0.03	0.05	0.02	0.00	0.01	0.04	0.05	0.06	0.03
C_{13}	0.02	0.02	0.07	0.04	0.06	0.09	0.02	0.04	0.07	0.00	0.01	0.04	0.04	0.06	0.09	0.01	0.02	0.05	0.01	0.01	0.05	0.03	0.03	0.05	0.02	0.05	0.05	0.00	0.01	0.04	0.03	0.04	0.06
C_{14}	0.00	0.00	0.04	0.00	0.01	0.04	0.02	0.03	0.06	0.00	0.01	0.04	0.00	0.01	0.05	0.01	0.02	0.05	0.00	0.01	0.04	0.02	0.02	0.05	0.02	0.04	0.07	0.01	0.01	0.04	0.02	0.03	0.05
C_{15}	0.01	0.01	0.06	0.02	0.04	0.06	0.03	0.05	0.07	0.01	0.02	0.05	0.00	0.01	0.04	0.01	0.02	0.05	0.02	0.04	0.07	0.03	0.04	0.07	0.01	0.03	0.02	0.00	0.01	0.04	0.03	0.04	0.03
C_{16}	0.05	0.05	0.09	0.03	0.05	0.08	0.02	0.03	0.06	0.03	0.05	0.08	0.02	0.04	0.07	0.00	0.01	0.04	0.03	0.06	0.09	0.03	0.04	0.07	0.02	0.05	0.03	0.02	0.04	0.03	0.03	0.03	0.05
C_{21}	0.03	0.03	0.08	0.05	0.07	0.06	0.02	0.03	0.06	0.03	0.03	0.06	0.06	0.03	0.05	0.02	0.04	0.07	0.05	0.06	0.08	0.01	0.01	0.04	0.01	0.03	0.02	0.01	0.02	0.04	0.03	0.05	0.03
C_{31}	0.03	0.03	0.08	0.03	0.05	0.07	0.00	0.01	0.04	0.03	0.04	0.07	0.03	0.05	0.08	0.03	0.05	0.08	0.03	0.05	0.08	0.03	0.03	0.05	0.02	0.05	0.04	0.02	0.04	0.06	0.01	0.03	0.06
C_{32}	0.03	0.03	0.08	0.02	0.05	0.07	0.01	0.02	0.05	0.02	0.03	0.07	0.02	0.05	0.08	0.02	0.04	0.07	0.02	0.05	0.08	0.01	0.03	0.05	0.01	0.02	0.03	0.05	0.07	0.04	0.04	0.06	0.08
C_{33}	0.03	0.03	0.07	0.01	0.03	0.05	0.04	0.02	0.04	0.05	0.07	0.08	0.03	0.04	0.08	0.02	0.03	0.06	0.03	0.04	0.07	0.03	0.03	0.05	0.04	0.07	0.08	0.00	0.01	0.03	0.02	0.05	0.04
C_{34}	0.02	0.02	0.06	0.03	0.05	0.08	0.02	0.04	0.07	0.04	0.04	0.08	0.02	0.04	0.07	0.01	0.03	0.06	0.04	0.05	0.08	0.03	0.03	0.06	0.02	0.04	0.06	0.02	0.04	0.07	0.01	0.01	0.04

received. The industrial experts were from the Jahjarm bauxite mine of Iran. These questionnaires consisted of their impacting factors according to **Figure 3**. The experts were asked to evaluate the direct influence of factors located in the rows on the factors located in columns. In the following segment, the implementation of the fuzzy DEMATEL method for environmental impacting factors is described. By undertaking the aforementioned steps, matrix T is tabulated in **Table 3**.

By implementing the steps of the fuzzy DEMATEL method, the vectors of (r), and (c) are calculated for aspects, and the obtained results are presented in **Table 4**. Finally, the fuzzy and non-fuzzy weights were calculated using **Equation (9)** and the results are shown in **Table 5** and **Figure 5**.

Table 4: Results of total relationships matrix for impacting factors

Impacting factors	r	c
C_{11}	(0.26, 0.36, 0.62)	(0.22, 0.45, 0.73)
C_{12}	(0.24, 0.42, 0.59)	(0.26, 0.46, 0.72)
C_{13}	(0.21, 0.37, 0.67)	(0.22, 0.36, 0.68)
C_{14}	(0.12, 0.2, 0.51)	(0.21, 0.31, 0.65)
C_{15}	(0.15, 0.33, 0.56)	(0.3, 0.45, 0.77)
C_{16}	(0.28, 0.47, 0.69)	(0.15, 0.31, 0.64)
C_{21}	(0.29, 0.41, 0.59)	(0.29, 0.48, 0.8)
C_{31}	(0.26, 0.44, 0.72)	(0.26, 0.32, 0.59)
C_{32}	(0.26, 0.5, 0.71)	(0.23, 0.49, 0.45)
C_{33}	(0.3, 0.44, 0.66)	(0.15, 0.28, 0.47)
C_{34}	(0.26, 0.41, 0.72)	(0.32, 0.43, 0.54)

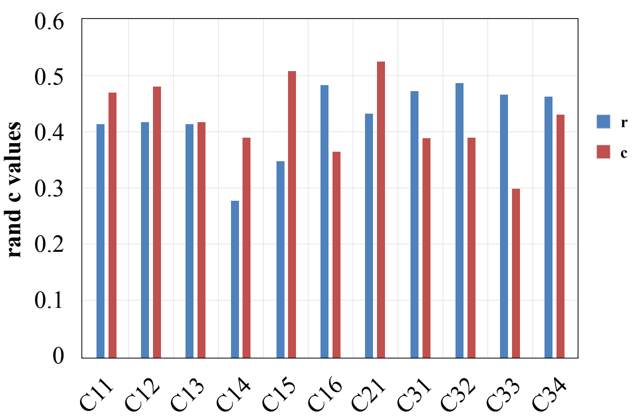

Figure 4: The r and c vectors for impacting factors

In is noted from **Table 4** and **Figure 4** the fixed price is the most total received influence among the impacting factors. Whereas skill and knowledge have a total received influence with the smallest (c) value. When the fixed price increases or decreases, other economic impacting factors will change. For example, when salary increases, the fixed price, employment of local work-

Table 5: The results of weighting on impacting factors

Impacting factor	Fuzzy weight	Deterministic weight (%)
C_{11}	(0.09, 0.09, 0.1)	9.37
C_{12}	(0.1, 0.1, 0.09)	9.67
C_{13}	(0.11, 0.08, 0.8)	9.10
C_{14}	(0.06, 0.06, 0.08)	6.80
C_{15}	(0.09, 0.09, 0.09)	9.04
C_{16}	(0.08, 0.09, 0.1)	8.89
C_{21}	(0.09, 0.09, 0.1)	9.43
C_{31}	(0.1, 0.1, 0.1)	9.93
C_{32}	(0.11, 0.11, 0.8)	9.66
C_{33}	(0.09, 0.08, 0.08)	8.26
C_{34}	(0.11, 0.1, 0.09)	9.85

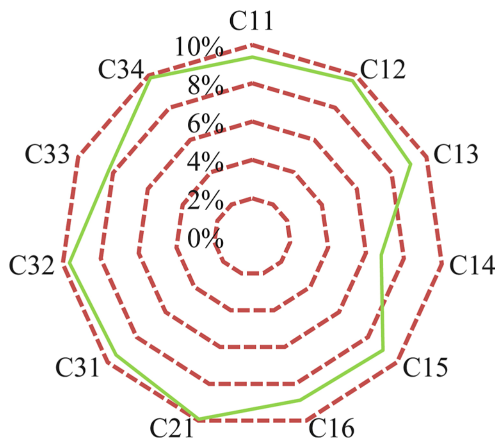

Figure 5: The impacting factors' weight

force, and local satisfaction will also increase, but early closure of the mine will decrease. For the same reason, the employment of a local workforce has the most total received influence, and the results also confirm this point. According to the calculations, early closure of the mine is the most total exerted influence. Whereas noise is the least total exerted influence factor since it does not increase or decrease any impacting factors.

As it can be concluded from **Table 5** and **Figure 5**, fixed price has the most weight. Whereas the noise is the impacting factor which has the minimum importance in the assessment of the system.

In order to introduce FDSDI, based on literature, the mining report, analysis and our own knowledge, standard guidelines for sustainable development mining, guidelines for Environmental Impact Assessment (EIA) for mining projects, and guidelines for social responsibility in outbound mining investments (**International Atomic Energy Agency (IAEA), 2006; Rwanda Environmental Management Authority (REMA), 2007; Department of Resources, Energy and Tourism, 2011; Vintro and Comajuncosa, 2010; Laurence et la., 2011; Sadler and Dalal-Clayton, 2012; Shen et al.,**

Table 6: Rating table of sustainable development impacting factors

impacting factor	Class				
	0	1	2	3	4
C_{11} (gr.m^3)	1>	1-5	5-10	10-20	>20
C_{12} (mg.l)	1>	1-3	3-5	5-7	>7
C_{13} (mg.kg)	10>	10-50	50-100	100-150	>150
C_{14} dB (A)	60>	60-75	75-85	85-95	>150
C_{15}	Very favourable		Fair		Very unfavourable
C_{16} (kWh.(t·km))	0.6>	0.6- 2.4	2.4-4.2	4.2-6	>6
C_{21} (%)	15>	15 -15.5	15.5-16	16-16.5	>16.5
C_{31} (%)	12>	12-20	20-28	>28	
C_{32}	Very favourable		Fair		Very unfavourable
C_{33}	Very unfavourable	Unfavourable	Fair	Favourable	Very favourable
C_{34}	Very favourable	Favourable	Fair	Unfavourable	Very unfavourable

2015; Anuru-yeng, 2019), all impacting factors were classified into five classes with respect to their role in SD. A corresponding rate of 0 to 4 was assigned to each class, and the score of each parameter is presented in **Table 6** for environmental, economic and social impacting factors, respectively.

FDSDI represents the Fuzzy DEMATEL Sustainable Development Index. The rating of FDSDI for sustainability is calculated as **Equation 10** (**Hudson 1992**):

$$\sum_{i=1}^{11} a_i \frac{P_i}{P_{Maxi}} \qquad (10)$$

Where:

a_i - the weight of i^{th} parameter,

P_i - the rate of i^{th} parameter (0 to 4),

P_{max} - the maximum rate of i^{th} parameter.

Using FDSDI computational procedure, the minimum and maximum possible ratings are 0 and 100, respectively. Sustainability was classified into three groups, depending on the value of FDSDI from low to high as listed in **Table 7**.

Table 7: sustainability classification based on FDSDI

FDSDI class	FDSDI	sustainability description
I	0-33	Low
II	33-66	Moderate
III	66-100	High

2.3. *Case study: Jahjarm bauxite mine*

The Jahjarm bauxite mine is located in the North Khorasan province, 19 km northeast of Jahjarm city. This mine has 18 zones named Golbini$_1$,…, Golbini$_8$ (G_1, G_2, …, G_8), Zou$_1$,…, Zou$_4$ (Z_1,.., Z_4), TaGoei1,…, TaGoei$_6$ (TG_1, TG_2, …, TG_6) and has more than 20 million tons of bauxite and it is Iran's largest bauxite mine. For every 3 tons of extraction, there are 2 tons of waste and 1 ton of ore. By and large, the bauxite zone of this mine has four types, as following:

(1) Upper kaolin bauxite;

(2) Hard bauxite;

(3) Soft shale bauxite; and

(4) Kaolin bauxite.

Figure 6: Location Jahjarm bauxite mines in Iran

Table 8: Calculation of FDSDI for zones of the Jahjarm bauxite mine

Item	Value of parameters											
a_i	9.37	9.67	9.10	6.80	9.04	8.89	9.43	9.93	9.66	8.26	9.85		
P_{imax}	4	4	4	4	4	4	4	4	4	4	4		
P_i	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}	C_{21}	C_{31}	C_{32}	C_{33}	C_{34}	FDSDI	FDSDI class
G_1	3	2	4	3	2	4	3	2	2	1	2	63.82	Moderate
G_2	3	3	3	3	4	4	3	3	4	3	2	79.76	High
G_3	3	2	3	3	2	4	3	3	2	3	3	70.29	High
G_4	3	3	3	2	2	3	3	2	2	2	3	64.32	Moderate
G_5	3	3	3	3	2	4	2	2	2	2	3	66.06	High
G_6	2	2	2	2	2	4	2	2	2	2	3	57.12	Moderate
G_7	3	3	3	3	4	3	3	3	2	3	4	77.59	High
G_8	3	4	3	3	4	4	3	3	4	3	4	87.10	High
Z_1	3	3	3	2	2	3	2	2	2	2	3	62.10	Moderate
Z_2	3	2	3	3	4	3	3	2	2	2	2	65.83	Moderate
Z_3	3	3	3	3	4	3	3	3	2	3	3	75.13	High
Z_4	4	4	2	2	4	4	4	4	2	3	4	85.01	High
TG_1	3	3	3	3	4	3	1	1	2	1	4	64.30	Moderate
TG_2	3	3	3	3	4	3	3	3	4	3	3	79.96	High
TG_3	3	3	3	3	2	3	1	1	2	2	4	61.68	Moderate
TG_4	3	3	3	3	2	4	3	3	2	3	3	72.71	High
TG_5	3	3	3	3	4	3	3	3	0	3	3	70.30	High
TG_6	3	2	3	2	4	4	1	1	0	3	2	56.82	Moderate

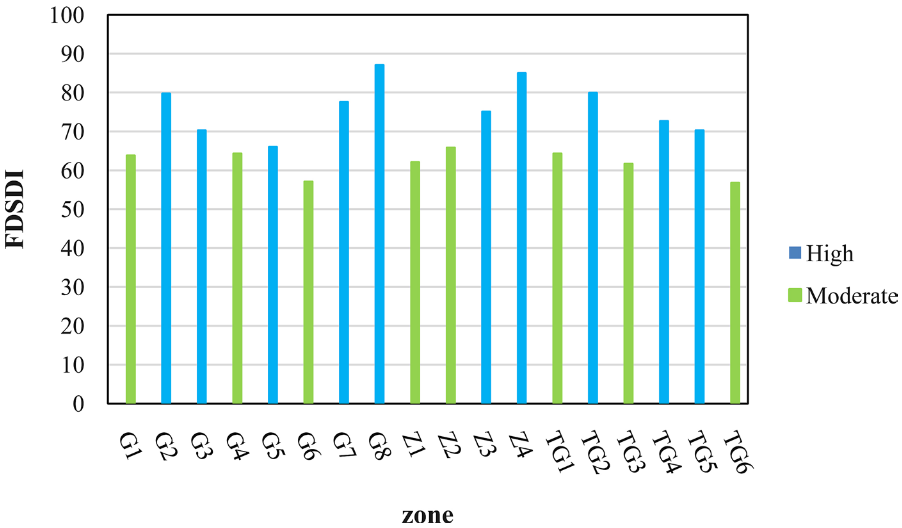

Figure 7: Calculation of FDSDI for the zones of the Jahjarm bauxite mine

The population of Jahjarm city is about 40,000. The climate of the Jahjarm Desert is cold and dry in the winter and hot in the summer. The minimum temperature is -6.5°C and the maximum is 36.5°C. The annual rainfall of the area is 179.7 mm and the relative humidity of the area is 84% and at least 4%. The wind direction of the area is mainly from the west, northwest and northeast. This area has unique vegetation, also known for its wildlife refuge where the Iranian cheetah lives. The mining area is a mountain range along the east-west part of the north of the Jahjarm Desert which is about 1000 meters above sea level. Generally, the stratigraphy and physical characteristics of the existing structures in the region as well as the structural stresses have played a key role in determining the geological status of the area. The location of the Jahjarm bauxite mine is shown in **Figure 6**.

3. Results and discussion

In the present article, a general approach was developed for an impact assessment of mining activities on SD by using the fuzzy DEMATEL method. For this purpose, 11 impacting factors were chosen that affect sustainability development; in the following the fuzzy DEMATEL was used to weight them and to create a classification system. Then, FDSDI determined the total score of the mine based on the offered class system. FDSDI values are between 0 and 100 and present the sustainability level in three classes from low to high level. This new index has been implemented in rating SD in the bauxite Jahjarm mine. Based on this index, as it can be seen in **Table 8 and Figure 7**, G_2, G_3, G_5, G_7, G_8, Z_3, Z_4, TG_2 TG_4, and TG_5 are at the highest level of sustainability, with values of 79.76, 70.29, 66.06, 77.59, 87.10, 75.13, 85.01, 79.96, 72.71, 70.30 respectively; and G1, G4, G6, Z1, Z2, TG1, TG3, and TG6 are at the moderate level of sustainability, with values of 63.82, 64.32, 57.12, 62.10, 65.83, 64.30, 61.68 and 56.82 respectively.

It is noteworthy that at present, this classification and indexing for determining the scope of the index in each class, also included evidence and events that occurred in each class in the past. In general, FDSDI is a useful scientific and systematic method for analyzing many parameters. Field experiences and observations show that the actual state of this mine is in accordance with the FDSDI approach. Therefore, in light of the results of this study, it can be concluded that FDSDI has high validity for the evaluation of SD in the Jahjarm bauxite mine. However, given the definitive definition of the intervals and the amount assigned to each interval (0 to 4) in **Table 6**, it is suggested that fuzzy logic be used to match the reality and reduce the uncertainty of the judgments in the results because this method allows you to determine the rate of each class and its intervals.

4. Conclusion

In the present study, a sustainable development index involving the fuzzy DEMATEL method was developed to evaluate the impacts of mining activities. The advantage of this approach compared with other studies include developing a sustainable development index assessment method based on the specific impacting factors for each mining project and considering the relative weight of each impacting factor in the assessment process. Also, to assess the sustainability of bauxite mining, its positive and negative impacts can be evaluated simultaneously. This general approach can be accomplished for each bauxite mining project, along with using specific impacting factors, based on the special conditions related to the mining method, and region conditions. This approach is suitable in assessing the status of SD in a bauxite mining region and specifying the priorities for improving the SD situation by determining the vulnerable and critical SD criteria. The proposed approach was implemented in the Jahjarm bauxite mine of Iran. The results indicated that its sustainability varies between 56.82 and 87.10. Accordingly, the best and worst zones are $Golbini_8$ and $TaGoei_6$, respectively. However, to achieve the main objective of SD, corrective measures with the priority of vulnerable criteria should be taken into account to improve this zone.

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SAŽETAK

Predstavljanje novoga indeksa održivoga razvoja u rudarstvu boksita metodom *fuzzy* DEMATEL

Rudarstvo kao ekonomska aktivnost može imati pozitivne i negativne učinke na zajednicu. Ti negativni učinci zajedno s nekim društvenim, ekonomskim i ekološkim utjecajima rudarske djelatnosti prijete ostvarenju ciljeva održivoga razvoja (SD). Stoga je procjena utjecaja na indekse održivoga razvoja važna za zaštitu rudarske djelatnosti u skladu s ciljevima održivoga razvoja. Stoga je predložena sustavna klasifikacija pomoću tehnike neodređenoga ispitivanja i laboratorija za ocjenjivanje (*fuzzy dematel*) tehnike za proučavanje i analizu jedanaest međusobnih odnosa faktora koji djeluju na otvorenim kopovima. Kako se ova tehnika temelji na mišljenju stručnjaka, primijenjeno je neizrazito kodiranje. Na taj je način izabrana težina utjecajnih čimbenika i povezana ocjena kako bi se razvio nov sustav klasifikacije. Na temelju predloženoga sustava ocjenjivanja uveden je novi indeks održivoga razvoja u rudarstvu boksita metodom *fuzzy* DEMATEL (FDSDI) za opis kvalitativne i kvantitativne razine na razini sustava. Primjena FDSDI-ja ispitivana je u rudniku boksita kao studija slučaja. Rezultati pokazuju da je FDSDI jednostavan i učinkovit alat za procjenu održivosti u iskopavanju boksita. Općenito, provedena tehnika predstavlja sustavan pristup za holističku analizu faktora utjecaja održivoga razvoja u rudnicima.

Ključne riječi:
ispitni i ocjenjivački laboratorij za odlučivanje, klasifikacijski sustav, zona, rudnik boksita Jahjarm

Authors contribution

Mohammad Ataei (Full Professor): initialized the idea, completed a literature review and participated in all work stages such as providing questionnaires designed to collect the necessary data, and distributed them among the experts. **Raziye Norouzi Masir** (Ph.D. Candidate): she did analysis of the data collected from the questionnaires. Also managed the whole process and supervised it from the beginning to the end.