Shahrood University of Technology
Iranian Society of Mining Engineering (IRSME)
Journal of Mining and Environment (JME)
journal homepage: www.jme.shahroodut.ac.ir
THOMSON REUTERS

A New Semi-Quantitative Approach to Open-Pit Mine Sustainability Assessment

Esmaeil Pouresmaeili, Arash Ebrahimabadi* and Hadi Hamidian

Department of Mining and Geology, Qaemshahr Branch, Islamic Azad University, Qaemshahr, Iran

Article Info

Received 18 October 2020
Received in Revised form 24 October 2020
Accepted 1 November 2020
Published online 3 November 2020

DOI:10.22044/jme.2020.10177.1954

Keywords

Sustainability Score
Open-Pit Mine
Sustainable Development
Macro-Factors

Abstract

Sustainability assessment has received numerous attentions in the mining industry. Mining sustainability includes the environmental, economic, and social dimensions, and a sustainable development is achieved when all these dimensions improve in a balanced manner. Therefore, to measure the sustainability score of a mine, we require an approach that evaluates all these three dimensions of mining sustainability. Some frameworks have been developed to compute the sustainability score of mining activities; however, some of them are very complicated and the others do not cover all the environmental, economic, and social aspects of sustainability. In order to fill this gap, this work was designed to introduce a practical approach to determine the score of mining sustainability. In order to develop this approach, initially, 14 negative and positive influential macro factors in the sustainability of open-pit mines were identified. Then the important levels of the factors were estimated based on the comments and scores of some experts. Two checklists were constructed for the negative and positive factors. The sustainability score was computed using these checklists and the importance levels of the factors. The score range was between -100 and +100. In order to implement the proposed approach, the Angouran lead and zinc mine was selected. The sustainability score of the Angouran mine was +47.91, which indicated that the mine had a sustainable condition. This score could increase through modification of some factors.

Abbreviation list

SD	Sustainable development
GDP	Gross domestic product
IRR	Internal rate of return
NFS_i	Negative factor score
PFS_j	Positive factor score
wn_i	Weighted importance values of negative factors
wp_j	Weighted importance values of positive factors
n	Number of factors
NS	Negative score
PS	Positive score
SS	Sustainability score
PC_j	Coefficients of positive factors
NC_i	Coefficients of negative factors

1. Introduction

With the advancement of technology, the human life standards have been improved, and the minerals have become very important to the human life and welfare. The high pace of population and urbanization growth further increases the requirement for minerals in the world. Consequently, the demand for minerals, especially metals, is rapidly increasing in the modern industrialized society. The mining industry is of crucial importance to many countries since it directly associates with the economic development. Australia is globally well-known not only for the export of gold, copper, silver, coal, uranium, natural gas, and oil but also for the production of precious stones such as diamonds. India is one of the world's top producers and exporters of diamonds, iron, zinc, and lead. Canada

✉ *Corresponding author: A.Ebrahimabadi@Qaemiau.ac.ir (A. Ebrahimabadi).*

is one of the major producers of natural gas in the world, and is prominent in the export of crude oil. In Canada, the energy extractive sector that consists of oil, gas, and mining companies is a key driver of the Canadian economy [5, 6].

Owing to a substantial increase in the mining activities over the last decades, more attention should be devoted to the issues of the sustainability of mining activities. A conceptual framework of sustainability, called the tripartite model, has been introduced. This framework is comprised of three dimensions, namely environmental, economic, and social dimensions. Based on this model, sustainability is achieved if the economic policies and strategies are equitable, sufficient social welfare is provided, and environmental systems are sustainable [3]. As a result, in order to explore the notion of sustainability that has a multidisciplinary nature, all environmental sciences, social sciences, and economic sciences are required to be addressed [4].

In the mining industry, among the three principles of sustainability, namely the environmental, economic, and social dimensions, dealing with the environmental issues or preserving the environment is a top priority [1,2] since the environment is adversely affected by the mining activities at all stages of mining operations. Nowadays, mineral production has reached 800,000 tonnes of ore per day in a mine [1, 2]. The increase in mineral production leads to the generation of more waste materials, and consequently, more land pollution. The extraction of low-grade minerals creates a considerable amount of waste materials and tailings. The environmental impacts of the exploration stage are much less than those of the exploitation stage. Similarly, in the production stage, compared with ore extraction, mineral processing causes a greater and more serious harm to the environment [7]. The economic aspect of mining, or mine economy, is another significant dimension of sustainability. If a proposed mining project is not sufficiently profitable, it is not economically reasonable to initiate that project. Social issues also play a critical role in the success of mining projects during their lifecycle. Through mining projects, some local job opportunities are provided in the mining areas, leading to an increase in the life expectancy of the local people. Therefore, knowing how to promote mining sustainability is vital for human beings, in general, and for those that are involved in mining activities in particular. Over the last decades, several researchers have drawn their attention to the assessment of the sustainability of mining projects. In this regard, in 2003, Folchi [8] proposed some criteria to rate the sustainable development (SD) of mines. In the Folchi approach, the score of each criterion, rather than that of each component, is calculated in a 10*10 matrix, and the final score of each component is computed by adding up the scores of all the criteria of that component. In 2011, Laurence [9] propounded a set of criteria for each sustainability principle. This large set of criteria provides a general framework, based on which, new methods of measuring the score of mining sustainability can be developed. Using the criteria proposed by Folchi and Laurence, some researchers have introduced several quantitative methods in order to estimate the score of mining sustainability [10-15]. Since the Folchi approach does not provide a final score for sustainability, Philips (2012, 2013) modified it and developed a new method. Also some studies undertaken on the mining sustainability have only focused on one or two principles of SD such as the environment or socio-economic dimensions [16-25]. Aznar-Sánchez *et al*. (2019) and Asr *et al*. (2019) have provided a comprehensive review of sustainable development in mining [26, 27]. Shang in 2019 investigated the socio-economic index of sustainability, and found that due to the mining activities in Mongolina for almost 15 years, the adult literacy and life expectancy were promoted by approximately 30% and 23%, respectively. However, this socio-economic progress was accompanied by a sharp rise in the environmental pressures between 1987 and 2015 [28]. In 2018, Cheng *et al*. examined soil contamination caused by heavy metals in the mining areas in Greece in the southwest of China. Identifying the source of heavy metal pollution in reserves is one of the most effective measures to prevent the environmental pollution. In their study, Cheng *et al*. took 40 samples from the surrounding areas of a lead and zinc mine, and analyzed eight elements including arsenic, cadmium, chromium, copper, mercury, nickel, and lead. They observed that the concentrations of arsenic, cadmium, lead, and zinc were higher than the permissible limit, and confirmed the negative effects of mining operations on the environment. The main sources of arsenic, cadmium, copper, lead, and zinc were the mining activities, coal particles produced in mining processing, and seasonal weather [29, 30].

In environmental management, the emphasis is laid on determining the potential environmental risks and effects and planning how to control them. In environmental management, all the issues associated with the mining life cycle, mineral processing, and supply chains as well as those influencing economy and society are taken into account for planning and decision-making. The top priority is to protect the natural resources of soil, water, and air. In order to preserve the natural resources of water, the release of the waste materials generated from mining activities into the surface and ground waters must not be prevented. The separation of acid-creating wastes and the use of mine dewatering systems are other effective strategies [31-34].

Most of the above-mentioned studies have merely considered one or two, not all, principles of sustainability; for instance, they have investigated either the environment or the economic dimension. Furthermore, the proposed methods provide no upper and lower bands for the sustainability score. In order to bridge these gaps, this work aimed at developing an approach to assess all the three principles of sustainability simultaneously. This approach determines not only the sustainability score of open-pit mines but also its lower and upper bands. As a result, the score obtained from this approach reflects the sustainability condition of a certain mine with respect to the possible lower and upper sustainability bands. In this approach, at first, the macro-factors affecting the sustainability of open-pit mines are identified and categorized into positive and negative factors. Then the sustainability score of a mine is measured using a scoring approach. In this scoring approach, the identified factors are rated based on the conditions of the mine. Some major differences between the proposed approach and the previous ones are as follow:

1- This approach is simpler and more practical, and the junior engineers can use it without much difficulty.
2- This approach includes both the negative and positive factors of sustainability.
3- This approach determines the degree of sustainability (unsustainability) and measures the sustainability score based on the qualitative assessment.

In order to implement the proposed approach, the Angouran lead and zinc mine was chosen for the case study analysis. The framework of the proposed approach is shown in Figure 1. In the next section, a full description of this approach is provided.

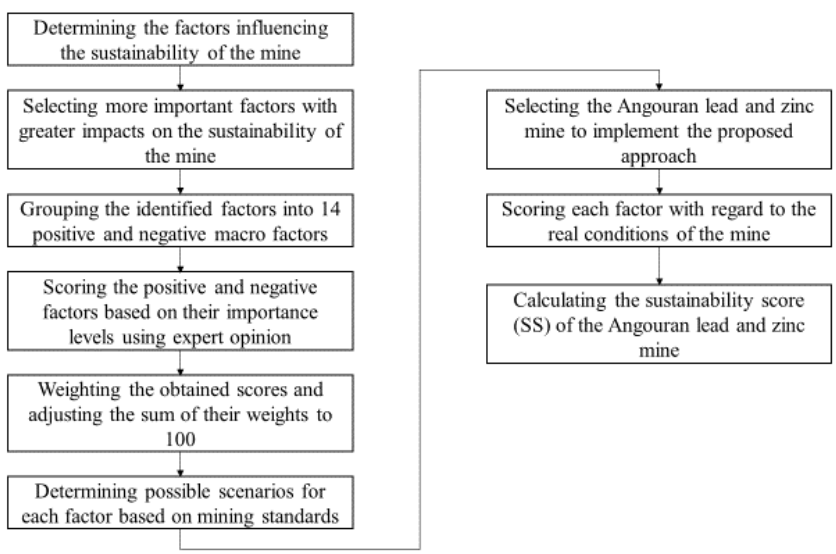

Figure 1. Framework of the proposed approach.

2. Methodology

This paper was designed to develop a new model for estimating the sustainability of open-pit mines. As mining has both the adverse and desirable effects on the surrounding areas, in this work, initially, the most significant positive and negative macro-impacts of mining activities on SD were identified. Then many influential SD factors related to each SD principle were extracted from the literature review. All these factors were categorized into 14 groups as macro-factors. These 14 macro-factors were further grouped into two parts: negative and positive factors. The negative factors were those adversely influencing sustainability, and the positive factors were those positively impacting sustainability. Through these macro-factors, all aspects of mining activities were considered in a simpler manner. Each one of these macro-factors is discussed below.

'Production costs' is a negative factor since the mine profitability rises when the operating costs decline. Generally, with an increase in the capital expenditure, the overall production costs reduce. Consequently, one way to decrease the adverse effects of this factor is to increase the capital expenditure. 'Production costs' is categorized as an economic factor.

'Resource depletion' results in the closure of mines and the unemployment of miners, and therefore, this factor of mining sustainability is considered negative. In order to measure its impact coefficient, three conditions were considered based on the time required for immigrating to a new place and finding a new job. 'Resource depletion' is associated with the socio-economic factor.

'Groundwater-surface water interface', as an environmental factor, is regarded as a negative factor of sustainability because mining can contaminate surface water and groundwater. Water pollution is a critical issue and leads to major problems, and thus it should be identified and controlled as soon as possible.

'Grade-tonnage uncertainty' directly influences the mine economy. Mine economy may not be desirable when the reserve grade estimation of the mine has a high variance. This problem can be solved by increasing the existing exploration data without considering the computational errors in the estimation process. 'Grade-tonnage uncertainty' is categorized as an economic factor.

Dust and gas, especially greenhouse gases, are emitted during all stages of mining activities such as drilling, blasting, loading, hauling, crushing, milling, and ore processing. In order to prevent air pollution, all mining sectors should use various strategies to control dust and gas emissions to the most extent. Some of these strategies are the use of renewable energy and the installation of gas filtration and water spraying systems in the mining processes. The use of water spraying machines is an effective way of dust control in mining, and enhances the health and safety of people in the mines and the surrounding areas. 'Dust-gas emission' is considered an environmental factor. Figure 2 shows the effect of water spray on dust emission.

(a) (b)

Figure 2. Effect of water spray on dust emission a) Before water spray and b) After water spray

'Annual waste tonnage production' refers to all the waste materials produced in the processing stages of mining each year. The waste and tailings are among the main sources of environmental pollution. Considering the scale of mining, the larger the mine is, the more environmental pollution it produces. Therefore, three conditions were defined for this factor based on the scales of mining.

'Vegetation coverage' is a negative factor as mining harms the vegetation coverage of the surrounding area of mines. The more the vegetation coverage in the area, the greater the destructive effect of mining on the ecology of the area. Hence, three conditions were considered for this factor based on the percentage of vegetation coverage [35].

From an economic perspective, 'income' is one of the most important factors that enhance SD. The amount of income depends on some elements such as the mineral prices and market demands. The investors are willing to invest in the mining projects whose Internal Rate of Return (IRR) is greater than their risk-free rate. With an increase in the investments, the total production costs decrease and profitability increases. Therefore, 'income', as an economic factor, was divided into three conditions in terms of the profitability of the mining projects.

'Reclamation', as a progressive activity in mining operations, is an essential part of modern mining. Through reclamation, the adverse environmental impacts of mining and its processing can be minimized. Reclamation also has some positive social effects, for instance, the restoration of the visual beauty of mining areas or the creation of new sceneries through landscape reclamation. 'Reclamation' is an environmental factor.

One of the most significant social effects of mining is the prevention of the local people from immigrating to other regions. Mines are usually located in remote areas where local people have difficulty finding a job. The implementation of mining projects in these areas opens up new job opportunities for these people. When local people, as the potential indigenous labor, are employed in these projects, their living condition gets better in those areas and they change their minds about immigration. Certainly, the larger the business is, the more the job positions are. The size of a business is determined by the number of workers. Thus three conditions were defined for this factor based on the scale of business sizes introduced by Statistics Canada in 2020 [36]. Having a job with a sufficient salary also increases the life expectancy of the local people and raises their living standards. Training local people improves their skills as well. Furthermore, implementing the mining projects requires numerous infrastructure and welfare facilities that are transferred to the mining areas. Accordingly, 'prevention of immigration' was divided into three conditions based on the number of job positions in the mining projects. Three conditions were defined for 'life expectancy' based on the regional living standards. 'Prevention of immigration' and 'life expectancy' are both regarded as the social factors. Additionally, three conditions were considered for 'job skill development in mining areas' based on the amount of time allocated for training local people, and three conditions were defined for 'infrastructure transfer to mine areas' regarding the existing infrastructures in mining areas. Mining has different shares of gross domestic product (GDP) in different countries. Some countries such as Chile have a great contribution of mining to GDP. Since in any country, each mine has a small share in the GDP of that country, in this work, the ratio of the annual mine income to the total mining sector share of GDP was used. In this way, the GDP values obtained from different scales were adjusted to a common scale, which promoted the comparability of the total mining shares of GDP. Considering that different mines have different values of GDP, 'GDP share of mining' was divided into three conditions.

The expert opinions are regarded as an effective way of SD assessment. In the present work, 12 mining experts working at university and in the industry were selected. A checklist including the negative and positive macro-factors of mining sustainability was prepared. Then these experts assigned a score out of 10 to each factor depending on the importance level of that factor. Table 1 presents the average scores given to the factors by the experts. The higher the score of the factor, the more important the factor. To weigh these scores, Equations 1 and 2 were utilized. The weighted importance values of the scores are reported in Table 2. The weights of all the scores were chosen such that their sum was equal to 100 (Equations 3 and 4).

$$wn_i = \frac{NFS_i}{\sum_{i=1}^{n} NFS_i} \times 100 \qquad (1)$$

$$wp_j = \frac{PFS_j}{\sum_{i=1}^{n} PFS_j} \times 100 \qquad (2)$$

$$\sum_{i=1}^{n} wn_i = 100 \qquad (3)$$

$$\sum_{j=1}^{n} wp_j = 100 \qquad (4)$$

where NFS_i is the negative factor score, PFS_j is the positive factor score, wn_i is the weighted importance values of the negative factors, wp_j is the weighted importance values of positive factors, and n is the number of factors.

Table 1. Importance levels of positive and negative factors influencing mining sustainability.

Impact	Factors	Average score
Negative	Production cost	8.32
	Resource depletion	7.64
	Groundwater-surface water interface	6.7
	Grade-tonnage uncertainty	4.22
	Dust-gas emission	5.3
	Annual waste tonnage production	6.14
	Vegetation coverage	6.3
Positive	Income	9
	Reclamation	7.2
	Prevention of immigration	6.34
	Infrastructure transfer to mine areas	6.9
	Life expectancy	5.7
	Job skill development in mining areas	5.7
	GDP share of mining	8.2

Note. The average score of each factor reflects the importance level of that factor out of 10

Table 2. Weighted importance values of the factors.

Impact	Factors	Weighted importance value
Negative	Production cost	18.65
	Resource depletion	17.12
	Groundwater-surface water interface	15.02
	Grade-tonnage uncertainty	9.46
	Dust-gas emission	11.88
	Annual waste tonnage production	13.76
	Vegetation coverage	14.12
Positive	Income	18.35
	Reclamation	14.68
	Prevention of immigration	12.93
	Infrastructure transfer to mining areas	14.07
	Life expectancy	11.62
	Job skill development in mining areas	11.62
	GDP share of mining	16.72

The importance level of each factor is the weight of that factor in the calculation of the sustainability score. Another checklist was prepared for the negative and positive factors in order to measure the sustainability score (Tables 3 and 4). In this checklist, three conditions were defined for each factor and a coefficient was given to each condition. The coefficients of zero, one, and 0.5 were assigned to the factors that had the minimum, medium, and maximum impacts on the SD of a mine, respectively.

Equations 5 and 6 were used to measure the sustainability scores of the negative and positive factors, respectively. Then the ultimate sustainability score of the mine was computed by Equation 7.

$$NS = \sum_{i=1}^{n} wn_i \times NC_i \tag{5}$$

$$PS = \sum_{i=1}^{n} wp_j \times PC_j \tag{6}$$

$$SS = NS - PS \tag{7}$$

where NS, PS, and SS are the negative score, positive score, and sustainability score, respectively, and wp_i and wn_i are the weighted importance values of the positive and negative factors, respectively. PC_j and NC_i are the coefficients of the positive and negative factors, respectively, and n is the number of factors.

Table 3. Sustainability checklist (Negative factors).

No.	Factor	Scenarios	Coefficient	Mine score
1	Production Cost	Production costs of the mine are more than the regional mining costs.	1	
		Production costs of the mine are approximately equal to the regional mining costs.	0.5	
		Production costs of the mine are fewer than the regional mining costs.	0	
2	Resource depletion	Life of the mine is fewer than 5 years. The employees do not have enough time, and they have to make plans to immigrate to a new place and find a new job in the near future.	1	
		Life of the mine is between 5 and 15 years. The employees have enough time, and they do not have to make plans to immigrate to a new place and find a new job anytime soon.	0.5	
		Life of the mine is more than 15 years. The employees do not have to make plans to immigrate to a new place and find a new job for a long time.	0	
3	Groundwater-surface water interface	Groundwater-surface water interface and water pollution are uncontrollable.	1	
		Groundwater-surface water interface and water pollution are controllable.	0.5	
		The mine interferes neither with surface water nor with groundwater.	0	
4	Grad-tonnage uncertainty	The grade and tonnage estimation has a large variance and the exploration plan is not good at all.	1	
		Grade and tonnage estimation has a medium variance and the exploration plan is not sufficiently good.	0.5	
		Grade and tonnage estimation has a little variance and the exploration plan is sufficiently good.	0	
5	Dust-gas emission	The mine and mill are not equipped with water spraying and gas filtration systems.	1	
		The mine and mill are equipped with a few water spraying and gas filtration systems.	0.5	
		The mine and mill are fully equipped with water spraying and gas filtration systems.	0	
6	Annual waste tonnage production	Annual tailing and stripped waste tonnage is greater than 5 million tonnes per year.	1	
		Annual tailing and stripped waste tonnage is between 1 and 5 million tonnes per year.	0.5	
		Annual tailing and stripped waste tonnage is less than 1 million tonnes per year.	0	
7	Vegetarian coverage	Vegetation cover scale is more than 60%.	1	
		Development of vegetation is moderate; the vegetation cover scale is 20%-60%.	0.5	
		Development of vegetation is low; the vegetation cover scale is less than 20%.	0	

3. Sustainability Assessment of Angouran Lead and Zinc Mine using Proposed Approach

The Angouran lead and zinc mine, as one of the oldest mines in Iran, is situated in the west part of the Zanjan province (Iran). To be exact, it lies 90 km west of the Zanjan city and 450 km northwest of Tehran. This mine, as the most prominent zinc producer in Iran, has a very high-grade non-sulfide Zn-(Pb–Ag) deposit. This deposit has a valuable, albeit intact, sulfide orebody. This mineral deposit possesses three main layers of oxide ores, sulfur ores, and mixed sulfide-oxide ores. The oxide ores and sulfur ores are in the upper and lower layers of the deposit, respectively, while the mixed sulfide-oxide ores are in the intermediate layer. In a study undertaken in 1999, it was found that the non-sulfide ore layer consisted of a resource of 14.6 Mt at 22.6% Zn and 4.6% Pb, and the sulfide ore layer comprised a resource of 4.7 Mt at 27.7% Zn, 2.4% Pb, and 110 (g/t) Ag using a cut-off grade of 4% zinc. This deposit is one of the most remarkable mineral deposits in the world regarding the ore quality. Figure 3 illustrates the location of the Angouran mine.

The proposed approach was used to determine the sustainability score (SS) of this mine. The two developed checklists were completed by the experts, and the gathered data were analyzed in order to calculate the sustainability score (SS) and determine how much this mine aligned with the SD principles. The conditions, relevant coefficients, weighted importance values, and sustainability scores of the negative and positive factors are presented in Tables 5 and 6, respectively.

Table 4. Sustainability checklist (Positive factors).

No.	Factor	Scenarios	Coefficient	Mine score
1	Income	IRR of the mining project is positive and more than the risk-free rate.	1	
		IRR of the mining project is positive and less than the risk-free rate.	0.5	
		IRR of the mining project is negative.	0	
2	Reclamation	Progressive reclamation plan has been implemented since the first stage of mining.	1	
		Progressive reclamation plan is implemented but it is behind schedule.	0.5	
		No reclamation plan is made.	0	
3	Prevention of immigration	The mining project is a large-sized business with more than 500 job positions.	1	
		The mining project is a medium-sized business with 100 to 499 job positions.	0.5	
		The mining project is a small-sized business with fewer than 99 job positions.	0	
4	Transfer infrastructure to mining areas	There is no infrastructure in the mining area and the mining sector constructs all the required infrastructures.	1	
		There are a few infrastructures in the mining area and the mining sector constructs other required infrastructures.	0.5	
		All the required infrastructures are available in the mining area and the mining sector uses those infrastructures.	0	
5	Life expectancy	Employees' salary is higher than the regional standard wage and their lifestyle is above the baseline of the regional standards of living.	1	
		Employees' salary is equal to the regional standard wage and their lifestyle is at the baseline of the regional standards of living.	0.5	
		Employees' salary is lower than the regional standard wage and their lifestyle is below the baseline of the regional standards of living.	0	
6	Job skill development in mining areas	An extensive amount of training is provided to the workforce.	1	
		A limited amount of training is provided to the workforce.	0.5	
		Training is not provided to the workforce, and skilled workers are hired from other areas.	0	
7	GDP share of mining	The mine has a share of more than 0.5% of the country's GDP.	1	
		The mine has a share of 0.1 to 0.5 percent of the country's GDP.	0.5	
		The mine has a share of less than 0.1% of the country's GDP.	0	

Table 5. Angouran sustainability checklist (negative factors).

No.	Factor	Condition	Coefficient (NC_i)	Weighted importance value (wn_i)	Sustainability score ($wn_i \times NC_i$)
1	Production cost	Production costs of the mine are less than the regional mining costs.	0	18.65	0
2	Resource depletion	Life of the mine is between 5 and 15 years. The employees have enough time, and they do not have to make plans to immigrate to a new place and find a new job anytime soon.	0.5	17.12	8.56
3	Groundwater-surface water interface	The mine interferes neither with surface water nor with groundwater.	0	15.02	0
4	Grade-tonnage uncertainty	Grade and tonnage estimation has a medium variance and the exploration plan is not sufficiently good.	0.5	9.46	4.73
5	Dust-gas emission	Mine and mill are not equipped with water spraying and gas filtration systems.	1	11.88	11.88
6	Annual waste tonnage production	Annual tailing and stripped waste tonnage is greater than 5 million tonnes per year.	1	13.76	13.76
7	Vegetation Coverage	Development of vegetation is low; the vegetation cover scale is less than 20%.	0	14.12	0
		Total negative score			38.93

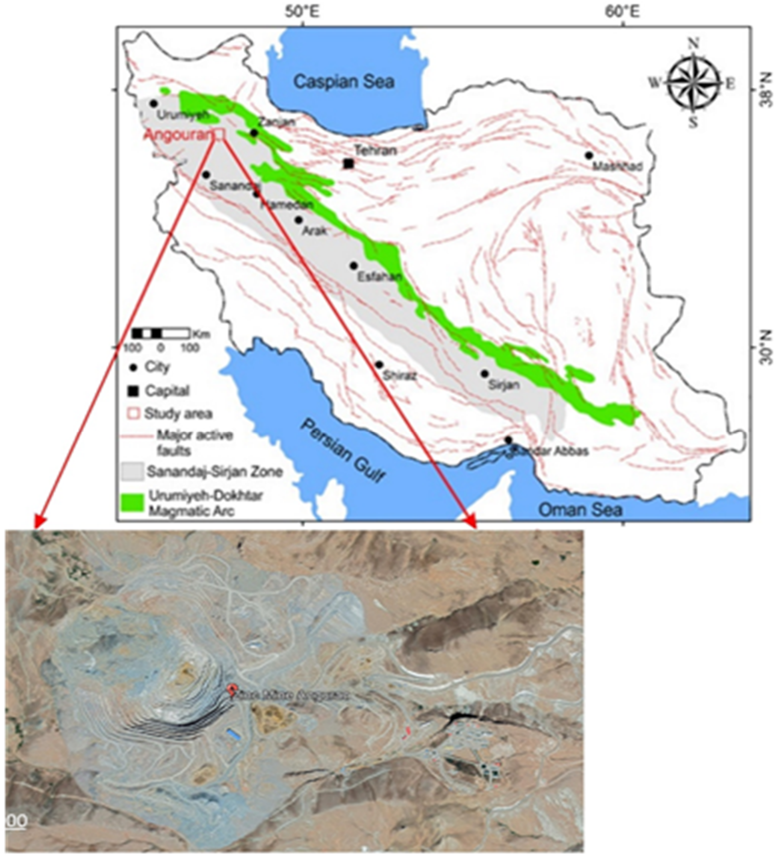

Figure 3. Location of the Angouran lead and zinc mine.

Table 6. Angouran sustainability checklist (positive factors).

No.	Factor	Condition	Coefficient (PC_j)	Weighted importance value (wp_j)	Sustainability score ($wp_j \times PC_j$)
1	Income	IRR of the mining project is positive and more than the risk-free rate.	1	18.35	18.35
2	Reclamation	Progressive reclamation plan is implemented but it is behind schedule.	0.5	14.68	7.34
3	Prevention of immigration	The mining project is a large-sized business with more than 500 job positions.	1	12.93	12.93
4	Infrastructure transfer to mine areas	There is no infrastructure in the mine area and the mining sector constructs all the required infrastructures.	1	14.07	14.07
5	Increase in life expectancy	Employees' salary is equal to the regional standard wage and their lifestyle is at the baseline of the regional living standards.	1	11.62	11.62
6	Job skill development in mining areas	A limited amount of training is provided to the workforce.	0.5	11.62	5.81
7	GDP Share of mining	The mine has a share of more than 0.5% of the country's GDP.	1	16.72	16.72
		Total positive score			86.84

The total negative score was computed by adding the scores of the negative factors (Table 5). Likewise, the total positive score was measured by adding the scores of the positive factors (Table 6).

Ultimately, Equation 7 was used to estimate the final sustainability score. As shown in Table 7, SS of the Angouran mine was 47.91.

Table 7. Total negative score, total positive score, and sustainability score of Angouran lead and zinc mine.

Score	Formula	Value
Total negative score	$NS = \sum_{i=1}^{n} wn_i \times NC_i$	38.93
Total positive score	$PS = \sum_{j=1}^{n} wp_j \times PC_j$	86.84
sustainability score (SS)	$SS = NS - PS$	47.91

4. Results and discussion

In this paper, a simple and practical approach was proposed for assessing the mining sustainability. The sustainability scores a range from -100 to +100 in this approach. In the worst-case scenario, all the positive and negative factors have values of zero and 1, respectively, and the sustainability score is -100. Conversely, in the best-case scenario, all the positive and negative factors have values of 1 and zero, respectively, and the sustainability score is +100. Figure 4 shows the score range of sustainability. If the sustainability score of a mine falls within the red and yellow areas, the mine has an unsustainable condition. This state highlights the need for the revision of the effective positive and negative factors to enhance the sustainability of the mine. If the score of a mine is within the green area, the mine is sustainable, and to enhance this state and increase the sustainability score of the mine, the influential factors can be modified.

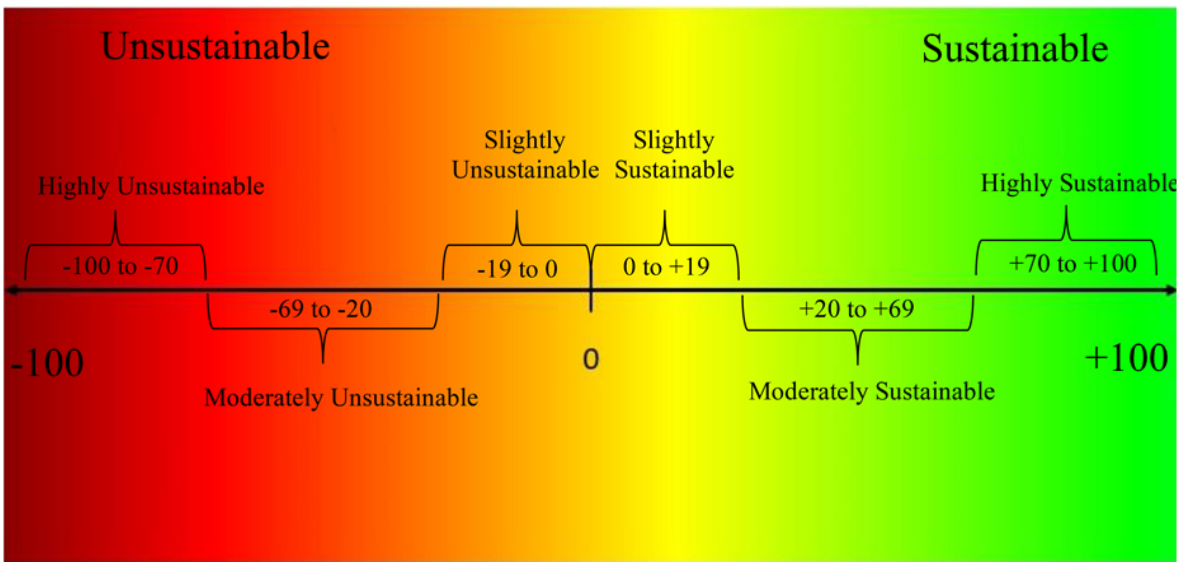

Figure 4. Range of mining sustainability scores.

The sustainability score of the Angouran mine (+47.91) is within the green area, indicating the sustainable condition of this mine. In order to improve its condition based on the SD principles, we should use effective strategies, for instance, conducting research on how to lessen the production costs and spending part of the income on making more exploration planning activities. The latter strategy may increase the life of the mine; nonetheless, it probably diminishes its grade-tonnage uncertainty. As another strategy, when the open-pit mine interferes with surface water or groundwater, the contaminating materials should be released in the areas far from these waters and the mining area should be constantly dried using proper drainage systems. Furthermore, the use of suitable and practical restoration plans can solve the issues associated with vegetation coverage and the scales of mining. Making efficient reclamation plans, training the workforce, increasing the income, and judiciously spending the income can increase the sustainability score of the Angouran mine.

5. Conclusions

Although the mining activities harm the environment, it develops the social and economic aspects of the human societies; consequently, the sustainability of mining activities is a critical issue. Numerous studies have been conducted to assess the sustainability of mining activities, and various approaches have been propounded to assess the sustainability of mines. Most of these approaches are difficult to implement. Unlike these approaches, the approach developed in this paper is simple and practical. Despite a surge of studies on the role of mining activities in the SD principles, just a handful of them have been undertaken on computing the score of sustainability development. In order to contribute to this line of research, this work developed a semi-quantitative approach to measure the open-pit mine sustainability score. In this approach, initially, the positive and negative macro-factors were identified and the importance levels of factors were estimated based on the comments and scores of some experts. Then two checklists for the negative and positive factors were formed and administered to the experts. Finally, the sustainability score of the mine was calculated using the importance levels of the factors and the coefficients obtained from the checklists. The obtained score ranged from -100 to +100. The easy implementation of this approach and the inclusion of all three dimensions of sustainable development were the two major advantages of this approach. The Angouran lead and zinc mine was selected to be analyzed. The results obtained reveal that this mine with a sustainability score of +47.91 is moderately sustainable (Figure 4). This score can increase through the modification of some factors such as the positive factors 2 and 6 and the negative factors 5 and 6.

References

[1]. Chakraborty, M.K., Ahmad, M., Singh, R.S., Pal, D., Bandopadhyay, C. and Chaulya, S.K. (2002). Determination of the emission rate from various opencast mining operations. Environmental Modelling & Software. 17 (5): 467-480.

[2]. Tadesse, S. (2000). Environmental Policy in Mining: Corporate Strategy and Planning for Closure. A contribution to published book (pp. 415-422). ISBN 1–56670-365-4.

[3]. Galdeano-Gómez, E., Aznar-Sánchez, J.A., Pérez-Mesa, J.C. and Piedra-Muñoz, L. (2017). Exploring synergies among agricultural sustainability dimensions: An empirical study on farming system in Almería (Southeast Spain). Ecological Economics, 140, 99-109.

[4]. Kajikawa, Y. (2008). Research core and framework of sustainability science. Sustainability Science. 3 (2): 215-239.

[5]. British Geological Survey. (2018). Available online: http://www.bgs.ac.uk/ mineralsUK/statistics/worldStatistics. html. (accessed on 30 October 2020).

[6]. U.S. Geological Survey. (2018). Available online: http://minerals.usgs.gov/minerals/. (accessed on 30 October 2020).

[7]. Hansen, Y., Broadhurst, J.L. and Petrie, J.G. (2008). Modelling leachate generation and mobility from copper sulphide tailings–An integrated approach to impact assessment. Minerals Engineering. 21 (4): 288-301.

[8]. Folchi, R. (2003, February). Environmental impact statement for mining with explosives: a quantitative method. In Proceedings of the annual conference on explosives and blasting technique (Vol. 2, pp. 285-296). ISEE; 1999.

[9]. Laurence, D. (2011). Establishing a sustainable mining operation: an overview. Journal of Cleaner Production, 19: (2-3), 278-284.

[10]. Phillips, J. (2012). Using a mathematical model to assess the sustainability of proposed bauxite mining in Andhra Pradesh, India from a quantitative-based environmental impact assessment. Environmental Earth Sciences, 67(6), 1587-1603.

[11]. Phillips, J. (2013). The application of a mathematical model of sustainability to the results of a semi-quantitative environmental impact assessment of two iron ore opencast mines in Iran. Applied Mathematical Modelling, 37(14-15): 7839-7854.

[12]. Rahmanpour, M. and Osanloo, M. (2017). A decision support system for determination of a sustainable pit limit. Journal of cleaner production, 141, 1249-1258.

[13]. Ebrahimabadi, A., Pouresmaieli, M., Afradi, A., Pouresmaeili, E. and Nouri, S. (2018). Comparing Two Methods of PROMETHEE and Fuzzy TOPSIS in Selecting the Best Plant Species for the Reclamation of Sarcheshmeh Copper Mine. Asian Journal of Water, Environment and Pollution. 15 (2): 141-152.

[14]. Pouresmaieli, M. and Osanloo, M. (2019, December). A Valuation Approach to Investigate the Sustainability of Sorkhe-Dizaj Iron Ore Mine of Iran. In International Symposium on Mine Planning & Equipment Selection (pp. 431-446). Springer, Cham.

[15]. Pouresmaieli, M. and Osanloo, M. (2019, November). Establishing a Model to Reduce the Risk of Premature Mine Closure. In IOP Conference Series: Earth and Environmental Science (Vol. 362, No. 1, p. 012005). IOP Publishing.

[16]. Antoniadis, V., Shaheen, S.M., Boersch, J., Frohne, T., Du Laing, G. and Rinklebe, J. (2017). Bioavailability and risk assessment of potentially toxic elements in garden edible vegetables and soils around a highly contaminated former mining area in Germany. Journal of environmental management, 186, 192-200.

[17]. Birch, C. (2017). Optimization of cut-off grades considering grade uncertainty in narrow, tabular gold deposits. Journal of the Southern African Institute of Mining and Metallurgy. 117 (2): 149-156.

[18]. Goodfellow, R.C. and Dimitrakopoulos, R. (2016). Global optimization of open pit mining complexes with uncertainty. Applied Soft Computing. 40: 292-304.

[19]. Bouchard, J., Sbarbaro, D. and Desbiens, A. (2018). Plant Automation for Energy-Efficient Mineral Processing. In Energy Efficiency in the Minerals Industry (pp. 233-250). Springer, Cham.

[20]. Wright, M., Tartari, V., Huang, K.G., Di Lorenzo, F. and Bercovitz, J. (2018). Knowledge worker mobility in context: Pushing the boundaries of theory and methods. Journal of Management Studies. 55 (1): 1-26.

[21]. Ranjan, V., Sen, P., Kumar, D. and Saraswat, A. (2017). Enhancement of mechanical stability of waste dump slope through establishing vegetation in a surface iron ore mine. Environmental Earth Sciences. 76 (1): 35.

[22]. Bridge, G. (2017). Mining and Mineral Resources. The International Encyclopedia of Geography.

[23]. Cuervo, V., Burge, L., Beaugrand, H., Hendershot, M. and Evans, S.G. (2017, May). Downstream Geomorphic Response of the 2014 Mount Polley Tailings Dam Failure, British Columbia. In Workshop on World Landslide Forum (pp. 281-289). Springer, Cham.

[24]. Martín-Crespo, T., Gómez-Ortiz, D., Martín-Velázquez, S., Martínez-Pagán, P., De Ignacio, C., Lillo, J. and Faz, Á. (2018). Geoenvironmental characterization of unstable abandoned mine tailings combining geophysical and geochemical methods (Cartagena-La Union district, Spain). Engineering Geology. 232: 135-146.

[25]. Amirshenava, S. and Osanloo, M. (2019). A hybrid semi-quantitative approach for impact assessment of mining activities on sustainable development indexes. Journal of Cleaner Production. 218: 823-834.

[26]. Aznar-Sánchez, J.A., Velasco-Muñoz, J.F., Belmonte-Ureña, L.J. and Manzano-Agugliaro, F. (2019). Innovation and technology for sustainable mining activity: A worldwide research assessment. Journal of Cleaner Production. 221: 38-54.

[27]. 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, 213-231.

[28]. Shang, C., Wu, T., Huang, G. and Wu, J. (2019). Weak sustainability is not sustainable: socioeconomic and environmental assessment of Inner Mongolia for the past three decades. Resources, Conservation and Recycling. 141: 243-252.

[29]. Cheng, X., Danek, T., Drozdova, J., Huang, Q., Qi, W., Zou, L. and Xiang, Y. (2018). Soil heavy metal pollution and risk assessment associated with the Zn-Pb mining region in Yunnan, Southwest China. Environmental monitoring and assessment. 190 (4): 194.

[30]. Ardejania, F. D., Shafaeia, S. Z., Moradzadeh, A., Marandi, R., Kakaei, R. and Shokri, B. J. (2008). Environmental problems related to pyrite oxidation from an active coal washing plant, Alborz Sharghi, Iran. In Mine Water and the Environment, 10th International Mine Water Association Congress (pp. 2-5).

[31]. Miranda, M., Chambers, D. and Coumans, C. (2005). Framework for responsible mining: a guide to evolving standards.

[32]. Parameswaran, K. (2016). Sustainability considerations in innovative process development. In Innovative Process Development in Metallurgical Industry (pp. 257-280). Springer, Cham.

[33]. Gorman, M.R. and Dzombak, D.A. (2018). A review of sustainable mining and resource management: transitioning from the life cycle of the mine to the life cycle of the mineral. Resour. Conserv. Recycl. 137, 281e291.

[34]. Jodeiri Shokri, B., Zare Naghadehi, M., Doulati Ardejani, F. and Hadadi, F. (2020). Probabilistic prediction of acid mine drainage generation risk based on pyrite oxidation process in coal washery rejects-A Case Study. Journal of Mining and Environment.

[35]. Zhang, Y., Lu, W.X. and Yang, Q.C. (2015). The impacts of mining exploitation on the environment in the Changchun–Jilin–Tumen economic area, Northeast China. Natural Hazards. 76 (2): 1019-1038.

[36]. Statistics Canada, Labor Force Survey; and ISED calculations (accessed 28 July 2020).

ارائه یک روش نیمه‌کمی جدید برای ارزیابی پایداری در معدن روباز

اسمعیل پوراسماعیلی، آرش ابراهیم‌آبادی* و هادی حمیدیان

گروه مهندسی معدن و زمین شناسی، واحد قائم شهر، دانشگاه آزاد اسلامی، قائم شهر، ایران

ارسال ۲۰۲۰/۱۰/۱۸، پذیرش ۲۰۲۰/۱۱/۰۱

نویسنده مسئول مکاتبات: A.Ebrahimabadi@Qaemiau.ac.ir

چکیده:

امروزه توسعه پایدار توجه زیادی در صنعت معدنکاری را به خود اختصاص داده است. پایداری در معدن شامل ابعاد زیست محیطی، اقتصادی و اجتماعی است و هنگامی که همه این ابعاد به صورت متعادل ارتقا یابد، توسعه پایدار در معدن حاصل می‌شود. بنابراین، برای اندازه گیری امتیاز پایداری یک معدن، به روشی نیاز است که تمام جوانب این ابعاد در معدنکاری را مورد ارزیابی قرار دهد. برخی از روش‌ها برای محاسبه امتیاز پایداری در فعالیت‌های معدنکاری ایجاد شده‌اند. با این حال، برخی از آنها بسیار پیچیده هستند و برخی دیگر همه جنبه‌های زیست محیطی، اقتصادی و اجتماعی را پوشش نمی‌دهند. به منظور پر کردن این شکاف، در این مقاله به معرفی یک روش عملی برای تعیین امتیاز پایداری معدن پرداخته شده است. به منظور توسعه این روش، ابتدا ۱۴ عامل کلی تأثیرگذار منفی و مثبت در پایداری معادن روباز شناسایی شدند. سپس میزان اهمیت این عوامل بر اساس نظر خبرگان تعیین شد. دو چک لیست برای عوامل منفی و مثبت ساخته شد (یکی برای عوامل مثبت و دیگری برای عوامل منفی). امتیاز پایداری با استفاده از این چک لیست‌ها و میزان اهمیت عوامل محاسبه شد. دامنه امتیاز در این روش بین ۱۰۰- و ۱۰۰+ است. به منظور اجرای روش پیشنهادی، معدن سرب و روی انگوران به عنوان مطالعه موردی انتخاب شد. امتیاز پایداری معدن انگوران ۴۷/۹۱ + بود که نشان داد معدن دارای شرایط پایداری مناسبی است. امتیاز پایداری می‌تواند از طریق اصلاح برخی از عوامل افزایش یابد.

کلمات کلیدی: امتیاز پایداری، معدن روباز، توسعه پایدار، عوامل کلی.