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Case Report

An evolution in sustainable development: Integrating new semi-quantitative assessment model with strategic management (Insights from the mineral sector)

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ABSTRACT

Sustainable development is crucial for ensuring the future of the environment, humanity, and industries. As a result, researchers across various disciplines have sought to expand sustainable practices within their fields. Since its introduction in 1992, sustainable development has made significant progress. Numerous models have been developed to assess sustainable development levels, with two-dimensional matrix-based models gaining the most attention. However, many of these models have two major limitations. First, they often need to specify the performance of individual indicators before they present the overall level of sustainability. Second, most models merely provide a sustainability score without offering a strategic plan to improve sustainability levels. In this article, we present a new model based on a two-dimensional matrix that addresses both of these issues. The model is generic, applicable across industries, and user-friendly. We applied this model to the mining industry, specifically at the Mehdi-abad mine, the second-largest lead and zinc mine in the world. The results showed the sustainability levels for the environmental, social, and economic indicators in the mine were 0.231, 0.23, and 0.016, respectively. The overall sustainability level, considering the weight of each indicator based on Iran's context, was 0.147. By following the strategic plan outlined in this study, which provides a clear path for sustainability improvement, the sustainability level of the mine could improve in the short, medium, and long term to 0.199, 0.387, and 0.553, respectively. This suggests that the mine's sustainability can progress from a poor level at the time of review to a good level in the long term with proper implementation of the suggested strategies, instilling reassurance and confidence in the model's effectiveness.

Abbreviation list

S: Sustainable development level	E: Environment
H_{NI}: Human Needs and Interests	A: Atmosphere
B: Biosphere	H: Hydrosphere
L: Lithosphere	Sd: Social development
Te: Technology	K: Knowledge
f: function	∝: Infinity
I: Individual	Comm: Community
Soc: Society	Sp: Species
NI: Needs and Interests	QL: Quality of Life
Ec: Economic	So: Social
BN: Basic Needs	Sh: Shelter
F: Food	W: Water
En: Energy	RepSp: Reproduction of Species

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(*continued*)

x_{ij}: entry of *i* and *j* in the matrix	*i*: raw in the matrix
j: column in the matrix	PS: Parameter Score
MP: Management Priority	St: Short term
Mt: Mid-term	Lt: Long term
PoC: Possibility of Control	IoC: Importance of Control
MPPC: Management Policy for Parameter Control	Env: Environmental
M: The results of the points given to each parameter in the two-dimensional	H_{NI1}: Human health and safety
H_{NI2}: Social relationship	H_{NI3}: Economic Component
FDM: Fuzzy Delphi Method	T: Total
SD: Sustainable Development	

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1. Introduction

Sustainable development (SD) is conceptualized based on the understanding of human-environment dynamics, human-environment relationships, and the mutual influence between humans and the environment. This includes the role of the environment in human development and how humans affect the surrounding environment, as well as the accumulation and application of knowledge in these areas [1]. The systematic and reciprocal relationships between human and ecological systems are understood through how humans perceive, conceptualize, and analyze the Earth's system [2].

Humans' understanding of the Earth system has led to the construction of a coherent framework that provides deeper insights into the interactions between the ecosphere (environment) and the anthroposphere (human society). In recent years, SD has made significant progress, especially since 2015 with the release of the Agenda 2030 [3] for SD. However, despite these advancements, the concept of SD is not yet fully understood in many industries and countries, particularly in underdeveloped and developing regions [2]. Therefore, a key first step is to examine the concept of SD carefully.

SD is a process that enables people to meet their needs and improve living standards without depleting natural resources or creating challenges for future generations [3,4]. The primary objectives of SD are to meet basic needs, improve living conditions, preserve ecosystems, and secure a safer and more prosperous future [5]. Globally, 'sustainability' refers to the ability of humans and the environment to coexist sustainably, considering the needs of the current generation while respecting the rights of future generations, protecting the environment, and minimizing harmful impacts [6].

SD seeks to address unsustainable practices in the economy, society, and environment. It provides solutions to challenges such as unsustainable population growth, poverty, and resource and environmental degradation [7,8]. Moreover, SD aims to achieve long-term economic and social goals by preserving natural resources, protecting the environment, and ensuring human health and welfare. SD encompasses three main pillars: the environment, society, and economy [1,3], and balancing these indicators is critical. By promoting economic growth, social progress, and environmental responsibility, SD helps human societies move toward a more sustainable, equitable, and viable future [2,9,10].

These models, despite being used as reference frameworks in evaluating SD in mines, have several fundamental flaws. The first and most important issue is that all of these models provide a single figure as the sustainability level, which cannot indicate which of the SD indicators has had the most significant positive or negative impact on the final result. Moreover, given the rapid technological advancements in recent years, new technologies and sciences have been introduced that could have a significant influence on the assessment of SD. Still, they should be more noticed in the existing models. Additionally, all these models merely provide a number representing the sustainability level, which presents challenges. This is because they do not indicate which actions should be taken on which indicators or parameters after the assessment to minimize negative impacts and maximize positive ones.

This study offers a semi-quantitative evaluation of SD in mining operations, introducing an enhanced sustainability assessment model that builds upon existing frameworks, particularly those by Folchi and Phillips [11,12]. In this context, the research questions derived from the mentioned introduction, which this article attempts to answer, are as follows.

1. Can the developed model assess the sustainability level for each of the indicators separately?
2. Is the developed model solely focused on providing a sustainability score for each indicator, or does it also offer an improvement plan?
3. Does the developed model take into account new technologies and scientific advancements that have emerged as a result of scientific progress?

To address the research questions, this paper presents a comprehensive model designed to assess sustainability levels for each indicator individually, offering an integrated strategic management improvement plan that incorporates new parameters driven by scientific advancements. The main objective is to propose a simple, adaptable model that can be applied across various industries by following the steps outlined and adjusting parameters to the specific context. The enhanced model's practical application is demonstrated through a case study at the Mehdiabad mine, the second-largest lead and zinc mine in the world, providing empirical validation and showcasing the model's effectiveness in assessing sustainability levels. Additionally, the involvement of stakeholders in the assessment process further distinguishes this study, making it more comprehensive than existing models. The novelty of this study lies in its expansion of traditional sustainability models by providing a more detailed evaluation focused on the three pillars of SD: environmental, social, and economic dimensions. Unlike previous models that offer a single, generalized sustainability score, this approach delivers separate evaluations for each indicator, offering a clearer understanding of sustainability levels, particularly in mining operations. A key innovation is the integration of strategic management principles, allowing for the development of short-, medium-, and long-term plans aimed at improving sustainability. In summary, the key contributions of this study include (1) the expansion of existing sustainability models to provide separate evaluations for each indicator, (2) the integration of strategic management principles into sustainability assessments, and (3) the empirical validation of the proposed model through a real-world case study.

Section 2 of this paper reviews the literature on sustainability assessment models. Since this model is designed to be applicable across industries, understanding the core concepts for its use, adaptation, and implementation is essential. Therefore, the literature review has been expanded to cover the key concepts employed in the developed model.

Section 3, the core of the paper, explains the developed model step-by-step. By adjusting certain variables, anyone familiar with SD concepts can adapt and apply the model to their specific industry.

Section 4 presents the model's results, provides an analysis, and offers a strategic plan for managing parameters to improve sustainability within a real-world case study. Section 5 applies the model to validate its performance under real-world conditions. Finally, Section 6 presents the paper's conclusion.

2. Literature review

SD has emerged as a critical framework for addressing the complex challenges of environmental degradation, socio-economic inequalities, and resource management, particularly in sectors like mining. Originally introduced by the World Commission on Environment and Development, chaired by Gro Harlem Brundtland, the concept of SD gained global prominence in the 1987 report *Our Common Future*, which emphasized the importance of meeting current needs without compromising the ability of future generations to meet theirs [3]. This foundational concept was further strengthened in 2015 during the SD Summit at the United Nations, where the 17 SD Goals (SDGs) and 169 associated targets were introduced. Known as Agenda 2030, this global initiative called on societies to align their strategies to achieve these goals by 2030 [13]. SD is often represented as a three-legged stool, symbolizing the interconnected pillars of environmental, social, and economic sustainability. This framework has since become a cornerstone in numerous studies and is widely referenced in sustainability literature [14].

In the mining sector, the literature on SD has evolved significantly, with various models developed to assess sustainability. Folchi (2003) proposed a framework for evaluating sustainability parameters, focusing primarily on the environmental impacts of mining activities [11]. This model has played a crucial role in providing a structured approach to assessing the ecological consequences of mining operations. Similarly, Phillips (2010) introduced a framework that evaluates the interrelationships between environmental and human systems, offering a quantitative foundation for sustainability assessments [13]. Phillips' model has been widely applied in case studies, demonstrating its utility in assessing mining sustainability [14]. However, while it provides a robust framework, it often produces a generalized sustainability score, which can obscure critical insights into specific sustainability dimensions. Like Folchi's model, the Phillips framework has limitations in offering a comprehensive view of sustainability, particularly in addressing social and economic factors.

Despite being considered the foundational model for assessing SD in mining, the validity of these models has remained the same due to technological advancements and increased awareness in the field of SD. Subsequently, other researchers have attempted to improve and expand these models based on current global conditions. One such improvement is the hybrid SD assessment model, which incorporated the dimension of time into existing models to provide a more contemporary and credible approach [15]. Later, another researcher sought to develop a model using multi-criteria decision-making methods and the Fulci and Phillips models, enabling the evaluation of each dimension of SD separately [16]. The complexity of the evaluation methods and the need for more consideration of the parameters stemming from technological growth, knowledge, and innovation are among the challenges faced by the models developed in recent years. Another study emphasized that societies require a comprehensive model for assessing SD, one that not only reports the valuable outcomes of previous models but is also versatile (easily adaptable for use across various industries by modifying certain parameters), simple, and capable of incorporating parameters arising from technological and knowledge advancements. This would allow the model to effectively demonstrate the impacts of these parameters on different aspects of SD [2].

The following are some examples of technological and knowledge advancements and their impacts on various aspects of SD. In 2022, researchers demonstrated that by employing phytoremediation technology and knowledge, soil contamination with heavy metals around mining sites could be reduced, which has a direct positive impact on the environment and public health [7]. Additionally, in a 2023 study, researchers investigated the impact of digitalization in mining on SD indicators and concluded that digitalization can reduce environmental impacts while enhancing socio-economic benefits [8]. Another study highlighted that using renewable energy in mining could decrease the uncertainty of mining projects by reducing reliance on fossil fuels while simultaneously increasing social awareness in mining communities by creating new jobs associated with the transfer of these technologies and mitigating environmental impacts [17]. All of these findings are directly related to the social responsibility of mining companies, which, alongside ensuring project profitability, enhance social satisfaction and reduce environmental impacts [18]. One of the latest studies introduced ecological knowledge to mining for the first time, showing that one of the main pathways to achieving SD in mining is education from an early age, as it directly influences human behavior towards nature [19]. Furthermore, the circular economy is now recognized as one of the most critical approaches for guiding mining communities toward SD by recycling mining products and waste. Therefore, focusing on the circular economy has become increasingly important in the pursuit of SD [20,21]. The application of strategic management with a SD approach has gained attention in various fields, including medicine, politics, systems management, water resource management, and digitalization. However, despite its fundamental importance, this concept still needs to be seriously addressed in the mining industry [22–25].

In summary, while existing models such as those proposed by Phillips and Folchi provide valuable frameworks for evaluating sustainability, they often need to capture the full spectrum of sustainability dimensions. This study aims to bridge that gap by expanding upon these models and introducing new parameters that reflect the interconnectedness of environmental, social, and economic factors. By applying this enhanced model to a real-world case study, the study provides empirical evidence of its effectiveness, contributing to the ongoing discussion on sustainable practices in the mining industry. This literature review underscores the relevance of the current study within the broader field of SD research. By addressing the limitations of existing models and emphasizing the importance of empirical validation and stakeholder engagement, this study aims to advance sustainability assessments in mining and create a framework adaptable to various contexts and conditions.

3. Method of SD assessment model

A new model incorporating fresh concepts in SD has been developed for the mining industry based on the three-legged stool framework. This model is the culmination of more than eight years of research and aims to provide a new perspective on SD. It offers a reimagined approach to the concepts found in previous SD models, such as those introduced by Folchi and Phillips [11–13,26,27].

In this section, we expand the two-dimensional model using the three-legged stool framework, which balances environmental, social, and economic sustainability. We then explain how the SD indicators are measured and the relationships between them. Finally, the model's visual output is presented, along with an explanation of how it is evaluated.

3.1. Base of a 3-legged stool

SD is widely recognized in academic literature and is often depicted using the "3-legged stool" metaphor, which emphasizes the balance between its three core pillars: Environment (E), Human Needs and Interests (HNI), which includes social aspects, and Economic factors in achieving SD (S) [13,27].

Each leg of the stool represents one of these essential dimensions—environmental, social, and economic. If any of these pillars is disproportionately developed, the overall stability of the SD system is compromised, making sustainability unachievable [26]. In this study, we build upon this well-established framework, using it as a basis to explore the dynamic interactions between these three components. Fig. 1 illustrates the SD model as a balanced system, dependent on the equilibrium of these interrelated pillars. To provide a more thorough exploration of this model, this section is divided into two sections.

- Section 3-1-1 focuses on the environmental (E) dimension, where the Earth's four critical environmental subsystems—atmosphere, biosphere, hydrosphere, and lithosphere are defined and their dynamic interactions explained. This section emphasizes how human activities affect the environment over time, shaping its sustainability.

Explores Human Needs and Interests (HNI), which includes social and economic aspects. This section highlights how human needs evolve due to technological advancements, social development, and knowledge growth. We also examine how increasing human demands can exceed the environment's capacity, ultimately threatening sustainability.

- Section 3-1-2 integrates the previous two concepts (E and HNI) to develop a comprehensive understanding of SD levels (S). It defines the necessary conditions for achieving positive sustainability, emphasizing that environmental capacity must exceed human demands for a system to remain sustainable over time.

By organizing the analysis into these sections, we aim to clearly differentiate between the environmental and human dimensions of SD

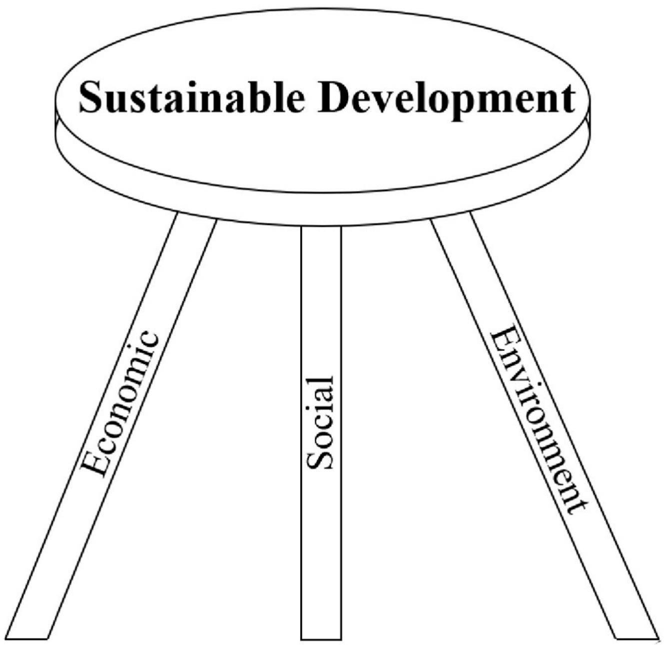


Fig. 1. sustainable development (3-legged stool).

while also explaining how they collectively influence the overall sustainability level. Each of these components plays a vital role in the holistic understanding of SD, and their interaction forms the foundation for evaluating sustainability within various projects and initiatives.

3.1.1. What's the connection between environment and human needs and interest in SD

The environment is generally classified into four main groups: atmosphere, biosphere, hydrosphere, and lithosphere [28]. Every activity of living organisms taking place on the earth affects at least one of these four groups. These groups act as a dynamic and integrated system, shaping E. It takes time (t) for each activity to impact E and evolve fully. Consequently, at any point in time, E can be defined as follows (equation (1)) [2,13]:

$$E(t) = (A + B + H + L) \tag{1}$$

Where E: Environment, A: Atmosphere, B: Biosphere, H: Hydrosphere, L: Lithosphere, and t: time.

According to the Darwinian theory of biological evolution, humans are capable of growing more than other species and have always attempted to satisfy their basic needs (BN) and their tangible and intangible needs and interests. This indicates that owing to the advancement of technology and knowledge, each generation has a greater number of needs and interests than the preceding generations. Human needs and interests (H_{NI}) are thus boundless and vary from one generation to another depending on social hierarchies [27] (equation (2)).

$$H_{NI}(t) = f[Sd, Te, K] \rightarrow \propto \tag{2}$$

Where HNI: Human Needs and Interests, Sd: Social development, Te: Technology, K: Knowledge, *f*: function, t: time, and ∝ : Infinity

H_{NI} is determined by accessible resources and provided services in E, ensuring tolerable conditions for human life and survival. If H_{NI} increases so incrementally that the services and resources expected from the environment exceed their capacity, humans gradually destroy E. From some point on, E would not be able to compensate for the damage caused by humans, and from that point on, humans are forced to seek another place to settle. In what follows, the interests and needs for which humans exploit E and the surrounding environment are provided [2] (equations (3)–(5)):

$$H_{NI}(t) = [I(NI), Comm(NI), Soc(NI), Sp(NI)] \tag{3}$$

$$NI(t) = [QL, Ec, So, BN] \tag{4}$$

$$BN(t) = [Sh, F, W, En, RepSp] \tag{5}$$

Where HNI: Human Needs and Interests, I: Individual, Comm: Community, Soc: Society, Sp: Species, NI: Needs and Interests, QL: Quality of Life, Ec: Economic, So: Social, BN: Basic Needs, Sh: Shelter F: Food, W: Water, En: Energy, and RepSp: Reproduction of Species.

3.1.2. Relation between SD (S) level determination and 3-legged stool

The concepts of E and H_{NI} were fully discussed in the previous sections. Here, these concepts are clarified in relation to SD. In order for the S level to be stable and positive at any point in time, the S level related to E should meet two fundamental conditions [12].

1. The S level of E must be positive at a certain time (equation (6)).
2. The amount of services and resources (H_{NI}) humans expect from E should be less than the potential and capacity of E at that time (equation (6)).

Then:

$$E(t) > H_{NI}(t) \Longleftrightarrow S(t) > 0 \tag{6}$$

However, when the level estimated for E is lower than or equal to the level of H_{NI}, humans' expectations (resources and services) from E (H_{NI}) at a certain time are greater than and, in the best-case scenario, equal to the capacity and resources of E. It may also show that the level of E at a certain time is zero or smaller than zero. Hence, it can be concluded that (equation (7)):

$$E(t) \leq H_{NI}(t) \Longleftrightarrow S(t) \leq 0 \tag{7}$$

Based on (equation (6) and (7)), it can be deduced that E is a veto factor in S evaluation. For a given project, when, for any reason, the level of E is not positive at a certain time, or the potential and capacity of E are equal to or smaller than H_{NI}, it can be stated that the project is practically unsustainable.

3.2. Implementation of a new SD assessment model based on 3-legged stool

SD evaluations are often conducted using matrix methods [11], grounded in the three-legged stool framework. In this study, we developed a two-dimensional matrix model incorporating semi-quantitative mathematical methods specifically designed for open-pit mines. The model aims to assess sustainability (S) and predict priority actions for managing key parameters in alignment with company management policies. This model captures the influence of significant factors on sustainability components (SCs) within a matrix of coefficients. One dimension of the matrix represents activities influencing SD, while the other includes the SD aspects affected by these activities [29]. The proposed model for sustainability assessment consists of three separate tables, each corresponding to one of the SD indicators: environmental (Env), economic (Ec), and social (So). The model allows for estimating the effect of industrial activities on SCs by rating factors and applying the matrix of coefficients [11]. First, the controllable parameters within each of the Env, Ec, and So tables are identified. Next, the importance of controlling each parameter is evaluated based on expert opinions. Finally, management priorities for controlling these parameters in the short, medium, and long terms are determined, considering company policies. The overall process for constructing the SD assessment model is illustrated in Fig. 2.

According to Fig. 2, the developed model was implemented step by

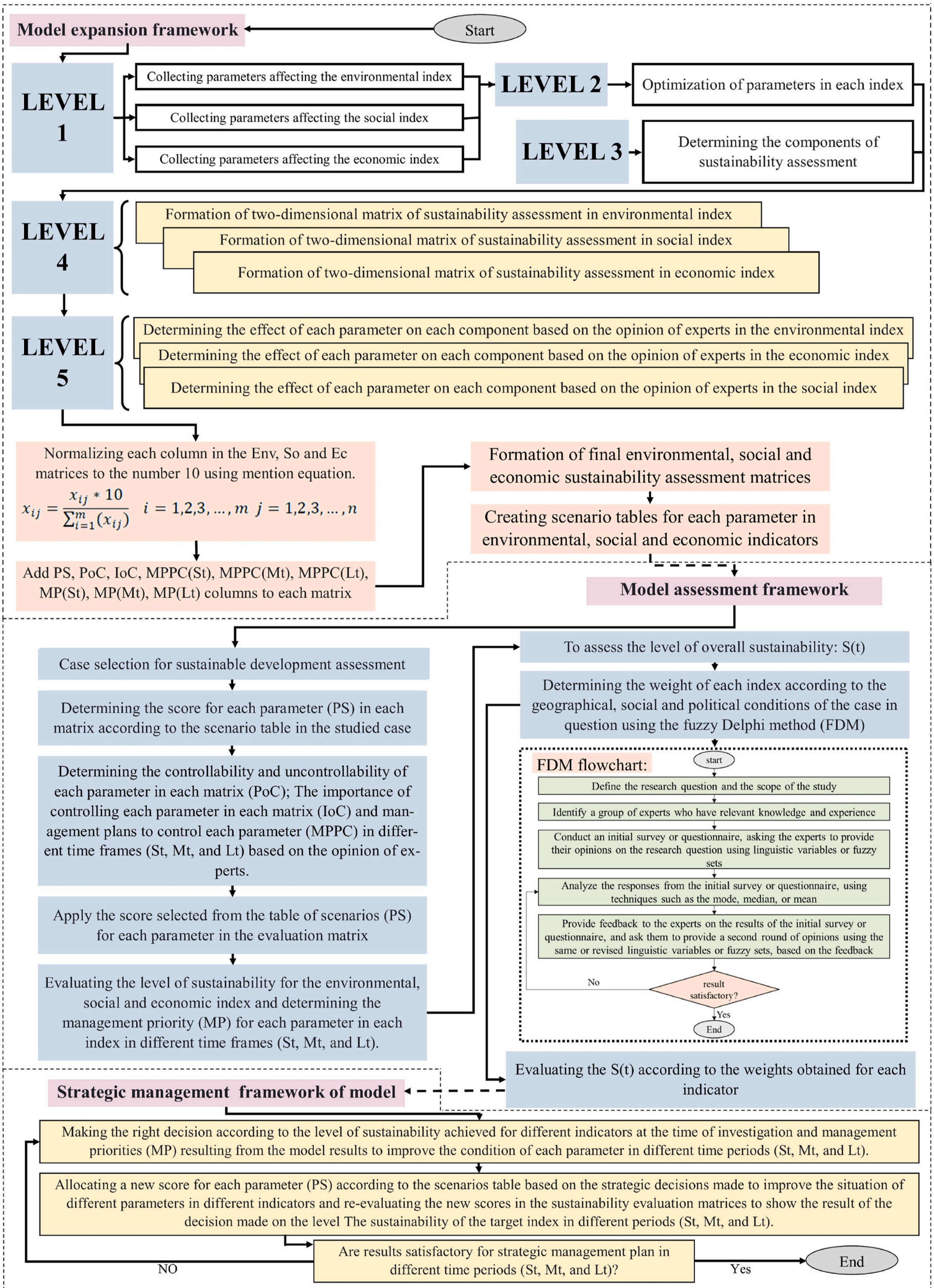


Fig. 2. Flowchart of developed model.

step in the mining industry. All the formulas needed to implement the model are mentioned below sections. Finally, the developed model was evaluated in a mine. To validate the model, the results obtained from the developed model were compared with a relatively similar model.

3.2.1. Influential parameters in the two-dimensional matrix model

In order to form two-dimensional S assessment matrices (the two-dimensional environmental, social, and economic matrix), the parameters affecting these matrices should first be identified. In the proposed model, a total of 54 SD parameters are detected from more than 150 parameters (Overlapping parameters were merged or deleted. Parameters that were in line with the UN definitions of SD (being in sync with today's technology), such as ecological literacy, use of the IoT, phytoremediation, renewable energy, etc., which were not present in the previous models, were added to this model) [2,30,31], containing 20 Env parameters, 18 So parameters, and 16 Ec parameters (Table 1). Due to their huge impact on all the indicators, some parameters, such as renewable energy, are included in all three indicators, and the effect of those parameters is separately assessed for each indicator.

Table 1
Influential parameters of three SD indicators in two-dimensional SD assessment matrices.

Influential parameters in Env indicator			
1	Renewable energy	11	Acid Mine Drainage (AMD)
2	IoT	12	Construction of suitable habitats to preserve animal species in the region
3	Ecological literacy	13	Geological conditions
4	Phytoremediation	14	Hydrological conditions
5	Interference with surface waters	15	Mining contractors
6	Interference with underground waters	16	Possibility of failure of tailing dam
7	Emission of greenhouse gases and dust	17	Reclamation
8	Noise	18	Change of land use
9	Ecological pollution	19	Fly-rock
10	Destruction of vegetation coverage	20	Tailing dam leakage
Influential parameters in So indicator			
1	Renewable energy	11	Creating environmental welfare for workers
2	IoT	12	Attention to issues related to the health of workers and mine employees
3	Ecological literacy		
4	Effect of mining machinery on traffic and road infrastructure of the region	13	Resource depletion
5	Training the workforce	14	Preservation of ancient heritage
6	Safety	15	Mining-related contractors
7	Use of skilled workforce	16	Employment, income, and life expectancy
8	Child labor avoidance	17	Importance of the region
9	Economic prosperity and employment in the mining region	18	Change of land use
10	Respecting the characteristics of Indigenous people in the mining region		
Influential parameters in Ec indicator			
1	Renewable energy	10	Discount rate
2	IoT	11	Profitability of mine
3	Effect of mining machinery on traffic and road infrastructure of the region	12	Operating costs
4	Economic prosperity and employment in the mining region	13	Uncertainty (ore reserve and grade)
5	Equipment (drilling, loading, and transporting equipment)	14	Demand
6	Resource depletion	15	Proportionality of workers' and employees' salaries to the difficulty of working in the mine
7	Employment, income, and life expectancy	16	Change of land use
8	Prices of products		
9	Government		

3.2.2. Scenario design for parameters and scoring process

After the parameters are identified for each indicator, scenarios should be devised for each parameter. Some parameters, like renewable energy, are involved in all three indicators; hence, for these parameters, three scenarios, each for one indicator (Env, So, and Ec), should be designed. Each scenario has a value from 0 to 10, which represents the amount of influence each parameter has in a given condition. A score of 0 denotes the highest positive effect, and a score of 10 indicates the highest negative effect (Table 2). Tables A1 to A.3 provide the scenarios related to each parameter in each indicator, along with the values of each scenario. These scenarios are devised based on the studies using the Fulci method, the studies on each parameter, and, in some cases, the studies on engineering decision-making. The studies associated with the design of these scenarios are available in Pouresmaili et al.'s studies [2, 12].

3.2.3. Sustainability components (SC)

The elements that are likely impacted by a mining unit are known as "sustainability components". The scientific community and SD researchers almost accept the components introduced in Folchi's model. For this purpose, we also used the same components. However, due to the direct impact of mining on the soil, in addition to the components introduced by Folchi, we also added soil quality to the SC. In Tables 3 and 12 SCs affected by the influential parameters are provided [11].

3.2.4. Construction of two-dimensional SD assessment matrices

The two-dimensional SD assessment model is defined based on the influential parameters in SCs. In order to estimate the impact of these parameters on each SCs, a questionnaire was prepared and evaluated by experts, including professors, engineers, and students. The characteristics of the experts participating in the evaluation of the two-dimensional matrix are reported in Table 4. The parameters of the indicators (Env, So, and Ec) were assessed in three separate tables, each for one indicator. The experts were asked to score the parameters in the range of 0–5 (0 = the least impact on SCs; 5 = the highest impact on SCs) (Table B1 to B.3).

After the evaluation of the two-dimensional matrices by the experts, the final assessment matrix was formed. The next step is to normalize all the columns in the three matrices to 10 through (equation (8)):

$$x_{ij} = \frac{x_{ij} * 10}{\sum_{i=1}^{m} (x_{ij})} \quad i = 1, 2, 3, \ldots, m \;\; j = 1, 2, 3, \ldots, n \tag{8}$$

Where i and j are row and column, respectively, in the matrix, and x_{ij} is the entry of i and j.

The final two-dimensional SD assessment matrix not only assesses the effect of various parameters on SCs but also offers other features. In these matrices, a column is added as a Parameter Score (PS) column. In this column, the score for each parameter is estimated by experts based on the scenarios specified for a given indicator, and the mine under study and the sustainability level of the case study are evaluated in the first part of the matrix. The second part of the final SD matrix is devoted to Management Priorities (MPs) for parameters in the short-term (St), mid-term (Mt), and long-term (Lt). For this purpose, the following columns are added to the final SD assessment matrices.

Table 2
Score ranges and their description in different scenarios.

Score range	Status
9–10	Very negative effect
7–8	negative effect
5–6	Neutral effect
3–4	positive effect
0–2	Very positive effect

Table 3
Sustainability components.

Environmental components	Social components	Economic component
Water quality	Social relations	Economy
Flora and fauna	Human health and safety	
Landscape		
Soil quality		
Air quality		
Above ground		
Noise		
Use of territory		
Underground		

Table 4
Demographic information of experts evaluating two-dimensional SD matrix.

Skill		Education	Number	Total Number
International Academia	Professor	Ph.D.	11	32 Experts
	Associate professor		1	
	Assistant Professor		1	
National Academia	Professor	Ph.D.	2	
	Associate professor		2	
	Assistant Professor		1	
Non-Academia member		Ph.D.	3	
		M.Sc.	6	
Student		Ph.D.	5	

- Possibility of Control (PoC) of parameters in the SD assessment matrix: This column indicates whether a given parameter can be controlled or not. Although some of the parameters introduced in the two-dimensional SD assessment matrices are out of control, their impact on the SD indicators should not be ignored. As a result, these parameters are evaluated as the main parameters in the SD assessment model. The value assigned to PoC is either 0 or 1. The former (0) represents the impossibility of controlling a parameter, and the latter (1) means the possibility of controlling a parameter.
- Importance of Control (IoC) of parameters: The IoC of parameters varies depending on the types of mineral materials, political, economic, and social conditions, local conditions, the geographical location of the mine, etc. Therefore, the IoC of the parameters that can be controlled is rated by experts considering the mine under study. The IoC values range from 0 (very little importance of controlling the parameter) to 10 (very high importance of controlling the parameter (Table C1).
- Management Policy for Parameter Control (MPPC): To control different parameters, each mining company may adopt different policy priorities based on local, national, and international laws and regulations, the management priority of the managers, the management policies of the mining complex, and the stakeholders' perspectives. Three columns are inserted for MPPC: 1) MPPC(St) for management policies that control parameters in the short term considering the prioritization of mining complex policies in the short term, 2) MPPC(Mt) for management policies that control parameters in the mid-term considering the prioritization of mining complex policies in the mid-term, and 3) MPPC(Lt) for management policies that control parameters in the long term considering the prioritization of mining complex policies in the long run. MPPC is scored by experts in the range of 0–10 for three periods of St, Mt, and Lt. The 0 value means that there is no priority and plan to control the parameter in the specified period. The ten value shows that controlling the parameter is considered a high priority by the mining complex and some plans are made to attain it (Table D1).

For the identified parameters, three columns are added to the table of the two-dimensional SD assessment matrix for MP in the three periods of St, Mt, and Lt. Assuming that uncontrollable parameters are constant in the three periods, MP for the mine under investigation can be obtained from (equations (9)–(11)) at the time of project evaluation (t) in these different periods:

$$\text{For St}: MP(St) = PS(t)^{*}PoC^{*}IoC^{*}MPPC(St) \quad (9)$$

$$\text{For Mt}: MP(Mt) = PS(t)^{*}PoC^{*}IoC^{*}MPPC(Mt) \quad (10)$$

$$\text{For Lt}: MP(Lt) = PS(t)^{*}PoC^{*}IoC^{*}MPPC(Lt) \quad (11)$$

Where MP: Management priority, PS: Parameter Score, PoC: Possibility of Control, IoC: Importance of Control, MPPC: Management Policy for Parameter Control, t: time, St: Short term, Mt: Mid-term, and Lt: Long term.

The computed values for MP in these periods vary from 0 to 1000. When a certain parameter has a higher MP value than other parameters in one of the periods (St, Mt, and Lt), controlling that parameter has more priority over controlling other parameters in that period. Therefore, the managers of the mine under study should give a high priority to control that parameter in that period. The final SD assessment tables for each of the Env, So, and Ec indicators with a management perspective are provided in Tables 5–7.

3.3. Mathematical model for S assessment of different indicators in mines

SD assessment matrices presented in "Tables 5–7" are used to calculate S. In these tables, only PS and SC columns are considered for the mathematical model of SD assessment. At first, experts evaluate each parameter and assign a score to it with respect to the designed scenarios. The score given to that parameter is added to the PS column. Then, the score given to the parameter is multiplied by the SCs related to that parameter. After the column summation of the SCs, the two-dimensional SD assessment matrices are prepared for the calculation of S via the mathematical model (the maximum score for each SC – measured by the column summation of each SC and the multiplication of the obtained value by the maximum score in PS – equals 100). The symbols in Table 8 are used in the mathematical estimation of S. The classification of SCs used in the calculations and equations is indicated in Table 9.

By using the information provided in "Tables 5–7" and the symbols and information presented in Tables 8 and 9, it is feasible to compute S for each indicator.

To achieve S in the two-dimensional matrix for the Env indicator (equations (12)–(16)), are utilized considering the table related to the Env indicator in Table 5.

$$M_{ij(Env)} = PS_i \times X_j \quad i = 1, 2, 3, \ldots, 20 \quad j = 1, 2, 3, \ldots, 12 \quad (12)$$

$$SC_{j(Env)} = \sum_{i=1}^{20} M_{ij} \quad (13)$$

$$E(t)_{(Env)} = \frac{\left[\left(\sum A_{Max} - \sum A\right) + \left(\sum B_{Max} - \sum B\right) + \left(\sum H_{Max} - \sum H\right) + \left(\sum L_{Max} - \sum L\right)\right]}{\sum A_{Max} + \sum B_{Max} + \sum H_{Max} + \sum L_{Max}} \quad (14)$$

Table 5
The final version of the two-dimensional SD assessment matrix for the Env indicator.

No	Parameter	The score is given to the desired parameter according to the available scenarios (PS)	Sustainable Components (SC)												The possibility of controlling the desired parameter (PoC)	The importance of controlling or improving the desired parameter according to the situation of the case study (IoC)	The policy of managers to control the desired parameter of case study in the short term (MPPC(St))	The policy of managers to control the desired parameter of case study in the mid-term (MPPC(Mt))	The policy of managers to control the desired parameter of case study in the long term (MPPC(Lt))	The management priority is to control the desired parameter of the case study in the short term (MP(St))	The management priority is to control the desired parameter of the case study in the mid-term (MP(Mt))	The management priority is to control the desired parameter of the case study in the long term (MP(Lt))
			Human health and safety	Social relationship	Water quality	Air quality	Use of territory	Flora and fauna	Above ground	Underground	Landscape	Noise	Economy	Soil quality								
1	Renewable energy		0.526	0.370	0.469	1.020	0.769	0.484	0.635	0.250	0.364	0.000	0.690	0.351	1							
2	IoT		0.658	0.185	0.625	0.816	0.000	0.161	0.635	1.000	0.364	0.000	0.690	0.702	1							
3	Ecological literacy		0.658	0.741	0.469	0.612	0.577	0.806	0.635	0.500	0.182	1.364	0.517	0.702	1							
4	Phytoremediation		0.395	0.185	0.625	0.408	0.192	0.806	0.476	0.250	0.545	0.000	0.172	0.877	1							
5	Interference with surface waters		0.526	0.556	0.781	0.204	0.577	0.484	0.635	0.500	0.545	0.455	0.517	0.526	1							
6	Interference with underground waters		0.526	0.556	0.781	0.204	0.385	0.323	0.317	1.000	0.364	0.455	0.517	0.526	1							
7	Emission of greenhouse gases and dust		0.526	0.556	0.469	1.020	0.385	0.484	0.317	0.250	0.545	0.455	0.517	0.351	1							
8	Noise		0.526	0.741	0.000	0.204	0.385	0.161	0.317	0.250	0.364	1.818	0.345	0.175	1							
9	Ecological pollution		0.658	0.741	0.625	0.816	0.577	0.645	0.476	0.500	0.545	0.455	0.690	0.526	1							
10	Destruction of vegetation coverage		0.395	0.556	0.469	0.612	0.385	0.645	0.635	0.250	0.727	0.909	0.517	0.526	1							
11	Acid Mine Drainage (AMD)		0.526	0.556	0.781	0.408	0.577	0.645	0.635	0.750	0.545	0.000	0.517	0.702	1							
12	Construction of suitable habitats to preserve animal species in the region		0.526	0.370	0.313	0.612	0.769	0.806	0.476	0.250	0.545	0.000	0.172	0.526	1							
13	Geological conditions		0.263	0.185	0.313	0.204	0.577	0.323	0.476	0.750	0.545	0.000	0.517	0.351	0	-	-	-	-	-	-	-
14	Hydrological conditions		0.263	0.185	0.469	0.408	0.577	0.323	0.476	0.750	0.364	0.000	0.517	0.351	0	-	-	-	-	-	-	-
15	Mining contractors		0.526	0.556	0.469	0.408	0.385	0.323	0.317	0.500	0.545	1.364	0.690	0.526	1							
16	Possibility of failure of tailing dam		0.658	0.741	0.625	0.408	0.769	0.645	0.635	0.500	0.727	0.000	0.690	0.526	1							
17	Reclamation		0.526	0.741	0.469	0.612	0.577	0.645	0.476	0.250	0.727	0.909	0.517	0.526	1							
18	Change of land use		0.263	0.370	0.469	0.408	0.577	0.484	0.476	0.750	0.727	0.909	0.517	0.526	0	-	-	-	-	-	-	-
19	Fly-rock		0.526	0.556	0.156	0.204	0.385	0.161	0.317	0.250	0.182	0.909	0.172	0.175	1							
20	Tailing dam leakage		0.526	0.556	0.625	0.408	0.577	0.645	0.635	0.500	0.545	0.000	0.517	0.526	1							
Total column			10	10	10	10	10	10	10	10	10	10	10	10								

Table 6
The final version of the two-dimensional SD assessment matrix for the So indicator.

No	Parameter	The score is given to the desired parameter according to the available scenarios (PS)	Sustainable Components (SC)												The possibility of controlling the desired parameter (PoC)	The importance of controlling or improving the desired parameter according to the situation of the case study (IoC)	The policy of managers to control the desired parameter of case study in the short term (MPPC(St))	The policy of managers to control the desired parameter of case study in the mid-term (MPPC(Mt))	The policy of managers to control the desired parameter of case study in the long term (MPPC(Lt))	The management priority is to control the desired parameter of the case study in the short term (MP(St))	The management priority to control the desired parameter of the case study in the mid-term (MP(Mt))	The management priority is to control the desired parameter of the case study in the long term (MP(Lt))
			Human health and safety	Social relationship	Water quality	Air quality	Use of territory	Flora and fauna	Above ground	Underground	Landscape	Noise	Economy	Soil quality								
1	Renewable energy		0.606	0.317	0.789	1.316	0.952	0.789	0.976	0.294	0.513	0.000	0.615	0.571	1							
2	IoT		0.758	0.159	1.053	1.053	0.000	0.263	0.976	1.176	0.513	0.000	0.615	1.143	1							
3	Ecological literacy		0.758	0.635	0.789	0.789	0.714	1.316	0.976	0.588	0.256	1.000	0.462	1.143	1							
4	Effect of mining machinery on traffic and road infrastructure of the region		0.455	0.635	0.263	0.789	0.476	0.789	0.488	0.294	0.513	1.333	0.462	0.571	1							
5	Training the workforce		0.606	0.476	0.526	0.526	0.476	0.263	0.244	0.588	0.513	0.667	0.615	0.286	1							
6	Safety		0.758	0.794	0.526	0.526	0.476	0.526	0.488	0.882	0.513	1.000	0.615	0.286	1							
7	Use of skilled workforce		0.758	0.635	0.789	0.789	0.238	0.789	0.244	0.294	0.513	1.000	0.615	0.286	1							
8	Child labor avoidance		0.758	0.794	1.053	1.053	0.714	1.053	0.732	0.882	0.769	1.000	0.615	0.571	1							
9	Economic prosperity and employment in the mining region		0.606	0.635	0.000	0.000	0.476	0.263	0.732	0.000	0.769	0.333	0.769	0.571	1							
10	Respecting the characteristics of indigenous people in the mining region		0.303	0.635	0.526	0.263	0.714	0.526	0.488	0.588	0.769	0.667	0.615	0.571	1							
11	Creating environmental welfare for workers		0.758	0.794	0.263	0.000	0.476	0.000	0.488	0.294	0.513	0.000	0.462	0.286	1							
12	Attention to issues related to the health of workers and mine employees		0.758	0.635	0.526	0.526	0.238	0.263	0.244	0.588	0.000	0.000	0.462	0.000	1							
13	Resource depletion		0.303	0.476	0.526	0.526	0.714	0.526	0.488	0.588	0.769	0.333	0.615	0.571	0	-	-	-	-	-	-	-
14	Preservation of ancient heritage		0.000	0.317	0.000	0.000	0.952	0.263	0.488	0.588	0.513	0.000	0.308	0.286	1							
15	Mining-related contractors		0.606	0.476	0.789	0.526	0.476	0.526	0.488	0.588	0.769	1.000	0.615	0.857	1							
16	Employment, income, and life expectancy		0.606	0.794	0.263	0.263	0.238	0.263	0.000	0.000	0.000	0.333	0.615	0.286	1							
17	Importance of the region		0.303	0.476	0.526	0.526	0.952	0.789	0.732	0.882	0.769	0.667	0.462	0.857	0	-	-	-	-	-	-	-
18	Change of land use		0.303	0.317	0.789	0.526	0.714	0.789	0.732	0.882	1.026	0.667	0.462	0.857	0	-	-	-	-	-	-	-
Total column			10	10	10	10	10	10	10	10	10	10	10	10								

Table 7
The final version of the two-dimensional SD assessment matrix for the Ec indicator.

No	Parameter	The score is given to the desired parameter according to the available scenarios (PS)	Sustainable Components (SC)												The possibility of controlling the desired parameter (PoC)	The importance of controlling or improving the desired parameter according to the situation of the case study (IoC)	The policy of managers to control the desired parameter of case study in the short term (MPPC(St))	The policy of managers to control the desired parameter of case study in the mid-term (MPPC(Mt))	The policy of managers to control the desired parameter of case study in the long term (MPPC(Lt))	The management priority is to control the desired parameter of the case study in the short term (MP(St))	The management priority to control the desired parameter of the case study in the mid-term (MP(Mt))	The management priority is to control the desired parameter of the case study in the long term (MP(Lt))
			Human health and safety	Social relationship	Water quality	Air quality	Use of territory	Flora and fauna	Above ground	Underground	Landscape	Noise	Economy	Soil quality								
1	Renewable energy		0.889	0.541	1.429	1.852	1.290	1.364	1.429	0.556	0.769	0.000	0.580	0.909	1							
2	IoT		1.111	0.270	1.905	1.481	0.000	0.455	1.429	2.222	0.769	0.000	0.580	1.818	1							
3	Effect of mining machinery on traffic and road infrastructure of the region		0.667	1.081	0.476	1.111	0.645	1.364	0.714	0.556	0.769	1.905	0.435	0.909	1							
4	Economic prosperity and employment in the mining region		0.889	1.081	0.000	0.000	0.645	0.455	1.071	0.000	1.154	0.476	0.725	0.909	1							
5	Equipment (drilling, loading, and transporting equipment)		0.889	0.270	0.476	1.111	0.323	0.455	1.071	1.111	0.385	1.905	0.725	0.455	1							
6	Resource depletion		0.444	0.811	0.952	0.741	0.968	0.909	0.714	1.111	1.154	0.476	0.580	0.909	0	-	-	-	-	-	-	-
7	Employment, income, and life expectancy		0.889	1.351	0.476	0.370	0.323	0.455	0.000	0.000	0.000	0.476	0.580	0.455	1							
8	Prices of products		0.444	0.270	0.000	0.000	0.645	0.000	0.000	0.000	0.000	0.000	0.725	0.000	0	-	-	-	-	-	-	-
9	Government		0.889	1.081	0.952	0.741	1.290	0.909	0.714	0.556	1.154	0.952	0.580	0.909	0	-	-	-	-	-	-	-
10	Discount rate		0.222	0.000	0.000	0.741	0.000	0.455	0.000	0.000	0.385	0.000	0.725	0.000	0	-	-	-	-	-	-	-
11	Profitability of mine		0.667	0.541	0.000	0.000	0.968	0.000	0.357	0.000	0.000	0.952	0.725	0.000	1							
12	Operating costs		0.444	0.270	0.476	0.000	0.000	0.455	0.357	0.000	0.000	0.952	0.725	0.455	1							
13	Uncertainty (ore reserve and grade)		0.000	0.270	0.476	0.370	0.645	0.455	0.357	1.111	0.385	0.000	0.580	0.000	1							
14	Demand		0.444	0.541	0.952	0.741	0.968	0.909	0.714	1.111	0.769	0.952	0.725	0.909	0	-	-	-	-	-	-	-
15	Proportionality of workers' and employees' salaries to the difficulty of working in the mine		0.667	1.081	0.000	0.000	0.323	0.000	0.000	0.000	0.769	0.000	0.580	0.000	1							
16	Change of land use		0.444	0.541	1.429	0.741	0.968	1.364	1.071	1.667	1.538	0.952	0.435	1.364	0	-	-	-	-	-	-	-
Total column			10	10	10	10	10	10	10	10	10	10	10	10								

$$H_{NI}(t)_{(Env)} = \frac{(H_{NI1} + H_{NI2} + H_{NI3})}{\sum H_{NI\ MAX}} \quad (15)$$

$$S(t)_{(Env)} = E(t)_{(Env)} - H_{NI}(t)_{(Env)} \quad (16)$$

To estimate S in the two-dimensional matrix for the So indicator (equations (17)–(21)), are used considering the table related to the So indicator in Table 6.

$$M_{ij(So)} = PS_i \times X_j \quad i = 1,2,3,\ldots,18 \quad j = 1,2,3,\ldots,12 \quad (17)$$

$$SC_{j(So)} = \sum_{i=1}^{18} M_{ij} \quad (18)$$

$$E(t)_{(So)} = \frac{\left[\left(\sum A_{Max} - \sum A\right) + \left(\sum B_{Max} - \sum B\right) + \left(\sum H_{Max} - \sum H\right) + \left(\sum L_{Max} - \sum L\right)\right]}{\sum A_{Max} + \sum B_{Max} + \sum H_{Max} + \sum L_{Max}} \quad (19)$$

$$H_{NI}(t)_{(So)} = \frac{(H_{NI1} + H_{NI2} + H_{NI3})}{\sum H_{NI\ MAX}} \quad (20)$$

$$S(t)_{(So)} = E(t)_{(So)} - H_{NI}(t)_{(So)} \quad (21)$$

To calculate S in the two-dimensional matrix for the Ec indicator (equations (22)–(26)), are utilized considering the table associated with the Env indicator in Table 7.

$$M_{ij(Ec)} = PS_i \times X_j \quad i = 1,2,3,\ldots,16 \quad j = 1,2,3,\ldots,12 \quad (22)$$

$$SC_{j(Ec)} = \sum_{i=1}^{16} M_{ij} \quad (23)$$

$$E(t)_{(Ec)} = \frac{\left[\left(\sum A_{Max} - \sum A\right) + \left(\sum B_{Max} - \sum B\right) + \left(\sum H_{Max} - \sum H\right) + \left(\sum L_{Max} - \sum L\right)\right]}{\sum A_{Max} + \sum B_{Max} + \sum H_{Max} + \sum L_{Max}} \quad (24)$$

$$H_{NI}(t)_{(Ec)} = \frac{(H_{NI1} + H_{NI2} + H_{NI3})}{\sum H_{NI\ MAX}} \quad (25)$$

$$S(t)_{(Ec)} = E(t)_{(Ec)} - H_{NI}(t)_{(Ec)} \quad (26)$$

The symbols in (equations (12)–(26)) are presented in Table 10. By calculating the S level of each indicator through the abovementioned equations and comparing the calculated value with those provided in Tables 10 and it is possible to determine the overall S of that indicator for the mine under study. Given the equations mentioned above, S can be in the range of −1 and +1 for each indicator (equation (16), (21) and (26)). The descriptions of different S ranges are shown in Table 10.

Given that one S value is estimated for each of the Env, So, and Ec indicators, three S values in the range of −1 and +1 are achieved. There are three ways to evaluate the overall SD level (S_T) of a mine.

1. Simple averaging (as the simplest method): The S value obtained for each indicator is divided by 3. The sum of the obtained values is the S_T of the mine at the time of project evaluation (t) (equation (27)).

$$S(t)_T = \frac{1}{3}S(t)_{(Env)} + \frac{1}{3}S(t)_{(So)} + \frac{1}{3}S(t)_{(Ec)} \quad (27)$$

2. Simple weighting: The weight of the indicator is determined by the number of parameters in that indicator. The S_T of the mine is obtained through simple weighting using (equation (28)).

$$S(t)_T = \frac{20}{54}S(t)_{(Env)} + \frac{18}{54}S(t)_{(So)} + \frac{16}{54}S(t)_{(Ec)} \quad (28)$$

3. Using Fuzzy Delphi Method (FDM): Countries differ in their political, economic, cultural, and social conditions. Therefore, each country gives different amounts of attention to different SD indicators. For instance, in underdeveloped countries, the most significant indicator is the Ec indicator, whereas in developed countries, much more attention is devoted to the Env and So indicators. The significance of indicators can also differ at a smaller geographical level. For example, in a country, in the areas where employment is in crisis, the So indicator has a higher priority than other indicators. In the protected environmental areas, the Env indicator gains much more importance than other indicators. Consequently, it is suggested that the weight of each indicator be determined separately based on the characteristics of the mining area and the political, social, economic, cultural, and ecological conditions of the mining country. In other words, to achieve S_T in different countries, the weight of each of the indicators should be estimated considering the political, social, economic, cultural, and ecological conditions of the mine under investigation on a local or national scale using expert opinion and FDM. In the present study, using the fuzzy Delphi method (the 7-point scale of triangular fuzzy number), the weights of each of the Env, So, and Ec indicators were estimated by six experts considering the current condition in Iran (equation (29)). Due to the large volume of this article, the mathematical relations and calculations related to

Table 8
Symbols used in the proposed mathematical model.

PS	Parameter Score	A	Atmosphere
X	Entry of Matrix	L	Lithosphere
M	The results of the points given to each parameter in the two-dimensional matrix	H_{NI1}	Human health and safety
SC	Sustainable Component	H_{NI2}	Social relationship
H_{NI}	Human Needs and Interests	H_{NI3}	Economic component
E	Environment	So	Social
S	SD level	Ec	Economic
B	Biosphere	Env	Environmental
H	Hydrosphere		

Table 9
SC classification.

SC	Symbol assigned to each SC	Maximum score in each category
Flora and fauna	Biosphere (B)	*B(Max)=1*100=100*
Water quality	Hydrosphere (H)	*H(Max)=1*100=100*
Air quality	Atmosphere (A_1)	*A(Max)=2*100=200*
Noise	A_2	
Use of territory	Lithosphere (L_1)	*L(Max)=5*100=500*
Above ground	L_2	
Underground	L_3	
Landscape	L_4	
Soil quality	L_5	
Human health and safety	Human Needs and Interests (H_{NI1})	$H_{NI}(Max)=3*100=300$
Social relationship	H_{NI2}	
Economy	H_{NI3}	

Table 10
S results in different conditions.

Result	Sustainability range	Condition
$S \leq 0$	$-1 \leq S \leq 0.000$	Unsustainable
$S > 0$	$0.001 \leq S \leq 0.250$	Weak sustainability
$S > 0$	$0.251 \leq S \leq 0.500$	Medium sustainability sustainability
$S > 0$	$0.501 \leq S \leq 0.750$	Good sustainability
$S > 0$	$0.751 \leq S \leq 1$	Excellent sustainability

this part are not given in the article and only the result is limited. But if the readers want to know how to weigh with FDM, they can read the mentioned article [19].

$$S(t)_T = 0.315S(t)_{(Env)} + 0.295S(t)_{(So)} + 0.39S(t)_{(Ec)} \tag{29}$$

4. Results, discussion and management strategies of the expanded model

Given the nature of SD (equation (6) and (7)), it is concluded that E is the veto factor in S assessment. To put it in other terms, if the So and Ec indicators of a mine have the maximum positive scores but the Env indicator is negative, the mine is unsustainable from the viewpoint of SD. In this section, first, the different states occurring for S_T are discussed (Table 11). All these states are examined assuming that the S value of the Env indicator (S_{Env}) is positive (when S_{Env} is negative, and it is crucial to continue mining activities, even if the S_{Ec} and S_{So} values are negative, policymakers should focus only on the Env indicator so as to improve the parameters associated with this indicator as soon as possible (St) and achieve a positive value for S_{Env}. Subsequently, they can direct their attention to enhancing the parameters of other indicators)

From the strategic management perspective, to raise S in mines after S assessment in various indicators, one of the abovementioned scenarios (Table 11) should be considered. It is also possible to predict S in different periods (St, Mt, and Lt) regarding the influential parameters. In this vein, some assumptions should be considered.

- When the overall level of SD (S_T) is negative, it is necessary to quickly make S_T positive in the short term St or, in some special cases, in the Mt by using the scenarios of state 2. Then, the parameters should be improved through the first scenario of state one so that after the re-evaluation of S, all the S values of the indicators fall within the acceptable range with respect to each other.
- When S_T is negative, the scenarios of state one should be used. If the S levels of the Ec and So indicators are negative, they should become positive as soon as possible in St and, in some special cases, in the Mt. After that, the parameters in the indicators should be upgraded through the first scenario of state one so that the S values of the indicators fall within the acceptable range with respect to each other.

Table 11
strategic management perspective for managing S level.

State 1: $S_T > 0$	1st scenario:	$S(t)_{(So)} > 0 \wedge S(t)_{(Ec)} > 0 \Rightarrow S(t)_{(So)} + S(t)_{(Ec)} + S(t)_{(Env)} > 0$
		In this scenario, all S values are positive for all the indicators. In this case, it is suggested that the indicator with the highest S level be initially identified. Then, the parameters of the other two indicators are improved using the evaluated MPs so that the S levels of these indicators fall within the same acceptable range as the S level of the superior indicator. After that, by considering the MPs for the parameters in the specified period, it is feasible to enhance all the indicators simultaneously, considering the available capacity and resources.
	2nd scenario:	$S(t)_{(So)} > 0 \wedge S(t)_{(Ec)} \leq 0 \Rightarrow S(t)_{(So)} + S(t)_{(Env)} > S(t)_{(Ec)}$
	3rd scenario:	$S(t)_{(So)} \leq 0 \wedge S(t)_{(Ec)} > 0 \Rightarrow S(t)_{(Ec)} + S(t)_{(Env)} > S(t)_{(So)}$
		These scenarios take place when the S level of the Ec or So indicator is zero or smaller than zero, and the S values of the other two indicators are positive. Under these conditions, the parameters with a high priority in the indicator with a zero or negative S value should be improved as soon as possible by considering the MPs of those parameters so that the S value of that indicator becomes positive. Then, given different S values of the indicators, the parameters should be improved based on MPs in the three time periods in such a way that the S values of these indicators are within the acceptable range with respect to each other.
	4th scenario:	$S(t)_{(So)} \leq 0 \wedge S(t)_{(Ec)} \leq 0 \Rightarrow S(t)_{(Env)} > S(t)_{(Ec)} + S(t)_{(So)}$
		This scenario occurs when the S values of the Ec and So indicators are zero or smaller than zero and the S value of the Env indicator is positive. In this case, the high-priority parameters in the Ec and So indicators should be identified and improved as soon as possible through the MPs of those parameters so that the S values of these indicators become positive. Subsequently, given different S values of the indicators, the parameters should be improved based on MPs in the three time periods in such a way that the S values of these indicators fall within the acceptable range with respect to each other.
State 2: $S_T < 0$	1st scenario:	$S(t)_{(So)} > 0 \wedge S(t)_{(Ec)} < 0 \Rightarrow S(t)_{(So)} + S(t)_{(Env)} \leq S(t)_{(Ec)} \Rightarrow S(t)_T \leq 0$
	2nd scenario:	$S(t)_{(So)} < 0 \wedge S(t)_{(Ec)} > 0 \Rightarrow S(t)_{(Ec)} + S(t)_{(Env)} \leq S(t)_{(So)} \Rightarrow S(t)_T \leq 0$
		These scenarios happen when the S value of the Ec or So indicator is zero or smaller than zero, and the S value is positive for the other two indicators. However, the S value of the Ec or So indicator is so negative that S_T becomes zero or negative. In these conditions, first, the high-priority parameters in the indicator with a negative S value should be identified and improved as soon as possible through the MPs of those parameters so that the S value becomes positive in that indicator. Then, given different S values of the indicators, the parameters should be improved based on MPs in the three time periods in such a way that the S values of these indicators fall within the acceptable range with respect to each other.
	3rd scenario:	$S(t)_{(So)} \leq 0 \wedge S(t)_{(Ec)} \leq 0 \Rightarrow S(t)_{(Env)} \leq S(t)_{(Ec)} + S(t)_{(So)} \Rightarrow S(t)_T \leq 0$
		This scenario takes place when the S values of the Ec and So indicators are zero or smaller than zero and the S value of the Env indicator is positive; nonetheless, the S values of the Ec and So indicators are so negative that S_T generally becomes zero or negative. In this case, the high-priority parameters in the negative indicators (Ec and So) should be identified and improved as soon as possible via the MPs of those parameters so that the S values of those indicators become positive. Afterward, given different S values of the indicators, the parameters should be improved based on MPs in the three time periods in such a way that the S values of these indicators fall within the acceptable range with respect to each other.

- The parameters that cannot be controlled or improved are assumed to remain constant over time (except for the 'resource depletion' parameter in the So indicator, whose score decreases over time if no new reserves are discovered).
- The PSs of parameters that can be controlled or improved cannot be reduced in the St, Mt, and Lt periods (they either remain constant or are boosted).

Table 12
Scores of parameters in Env, So, and Ec indicators in different periods for Mehdiabad Lead and Zinc Mine.

parameter	Score at (t)			Score at (St)			Score at (Mt)			Score at (Lt)		
	Env	So	Ec	Env	So	Ec	Env	So	Ec	Env	So	Ec
Renewable energy	10	10	10	10	10	8	7	7	6	7	4	3
IoT	10	10	10	10	10	8	7	7	6	7	4	3
Ecological literacy	2	3		2	3		1	2		1	1	
Phytoremediation	6			6			4			4		
Interference with surface waters	6			6			4			4		
Interference with underground waters	6			6			4			4		
Emission of greenhouse gases and dust	3			3			2			2		
Noise	2			2			1			1		
Ecological pollution	2			2			1			1		
Destruction of vegetation coverage	3			3			2			2		
Acid Mine Drainage (AMD)	0			0			0			0		
Construction of suitable habitats to preserve animal species in the region	2			2			1			1		
Geological conditions	3			3			3			3		
Hydrological conditions	3			3			3			3		
Mining contractors	3			3			2			2		
Possibility of failure of tailing dam	0			0			0			0		
Reclamation	5			5			4			4		
Change of land use	9	3	1	9	3	1	9	3	1	9	3	1
Fly-rock	4			4			3			3		
Tailing dam leakage	0			10			0			0		
Effect of mining machinery on traffic and road infrastructure of the region		3	4		3	3		2	2		1	1
Training the workforce		2			2			1			1	
Safety		5			5			4			2	
Use of skilled workforce		3			3			2			1	
Child labor avoidance		0			0			0			0	
Economic prosperity and employment in the mining region		2	3		2	2		1	1		1	1
Respecting the characteristics of indigenous people in the mining region		3			3			2			1	
Creating environmental welfare for workers		3			3			2			1	
Attention to issues related to the health of workers and mine employees		3			3			2			1	
Resource depletion		3	8		3	8		5	8		8	8
Preservation of ancient heritage		3			3			2			1	
Mining-related contractors		4			4			3			2	
Employment, income, and life expectancy		4			4			3			2	
Importance of the region		5			5			5			5	
Equipment (drilling, loading, and transporting equipment)			5			4			3			2
Employment, income, and life expectancy			3			2			1			1
Prices of products			4			4			4			4
Government			3			5			5			5
Discount rate			8			8			8			8
Profitability of mine			3			2			1			1
Operating costs			8			6			4			2
Uncertainty (ore reserve and grade)			3			2			1			1
Demand			0			0			0			0
Proportionality of workers' and employees' salaries to the difficulty of working in the mine			6			5			3			2

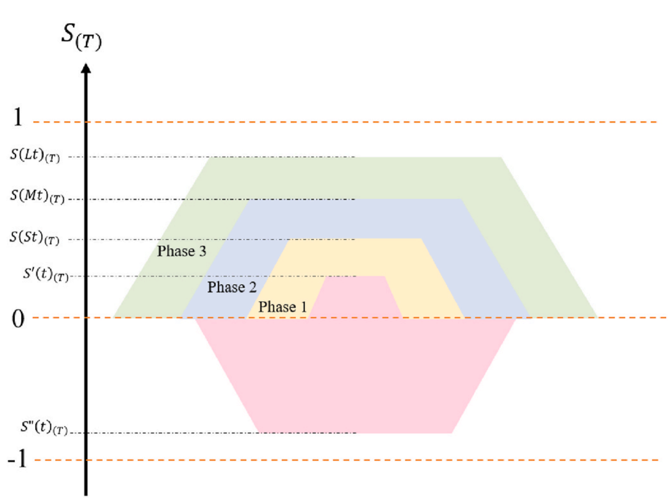


Fig. 3. Overall SD (S_T) perspective.

Considering these assumptions, the values given to the parameters (PSs), and the MPs determined for the St, Mt, and Lt periods, it is feasible to predict S in these periods. For example, based on the existing policies in the mine under study, experts can anticipate how much PSs given to the parameters in different indicators can be raised in the short term (PS (St)) and what value the parameters can achieve by following the scenarios designed for the St period. The same procedure can be employed for different periods. The predictions made in different periods for PSs, namely, PS(St), PS(Mt), and PS(LT), are included in the two-dimensional SD assessment matrix. Then, through (equations (12)–(26)), S can be predicted for different indicators in the periods of St, Mt, and Lt. Based on what was stated, it can be concluded that (equations (30)–(32)):

$$S(t)_{(Env)} \leq S(St)_{(Env)} < S(Mt)_{(Env)} < S(Lt)_{(Env)} \tag{30}$$

$$S(t)_{(So)} \leq S(St)_{(So)} < S(Mt)_{(So)} < S(Lt)_{(So)} \tag{31}$$

$$S(t)_{(Ec)} \leq S(St)_{(Ec)} < S(Mt)_{(Ec)} < S(Lt)_{(Ec)} \tag{32}$$

By determining the PS values in different periods, the S_T value of the

Table 13
Sustainability level of different indicators in different periods for Mehdiabad Lead and Zinc Mine.

	S(t)	S(St)	S(Mt)	S(Lt)
S_{Env}	0.231	0.231	0.441	0.62
S_{So}	0.23	0.23	0.408	0.569
S_{Ec}	0.016	0.149	0.327	0.487
S_T	0.147	0.199	0.387	0.553

mine is predicted through (equation (29)). The S_T values for different periods are obtained through (equation (33)).

$$S(t)_{(T)} < S(St)_{(T)} < S(Mt)_{(T)} < S(Lt)_{(T)} \tag{33}$$

In order for mine owners to gain a better understanding of S, an image illustrating an S perspective is provided. Fig. 3 gives a better insight into the status of S_T at the time of project evaluation (t) and displays the predicted S_T values in different periods (St, Mt, and Lt) for the mine under study. Fig. 3 can be modified to depict the S perspective of the Env, So, and Ec indicators.

The S_T perspective is conceptually exhibited in Fig. 3. When it comes to a real case (a mine), as seen in Fig. 3, S_T can be negative ($S''(t)_{(T)}$) or positive ($S'(t)_{(T)}$). The values obtained from (equation (29)) at the time of investigation (t) should be placed in Fig. 3. Then, given the predictions made for St, Mt, and Lt, the S levels for different periods are estimated and included in this figure. Fig. 3, along with Table 10 can offer mine owners a real perspective about what the status of the overall S level is at the time of project evaluation (t) and how it is going to change in different periods in the future. Fig. 3 can be expanded to predict S values for different indicators (Env, So, and Ec).

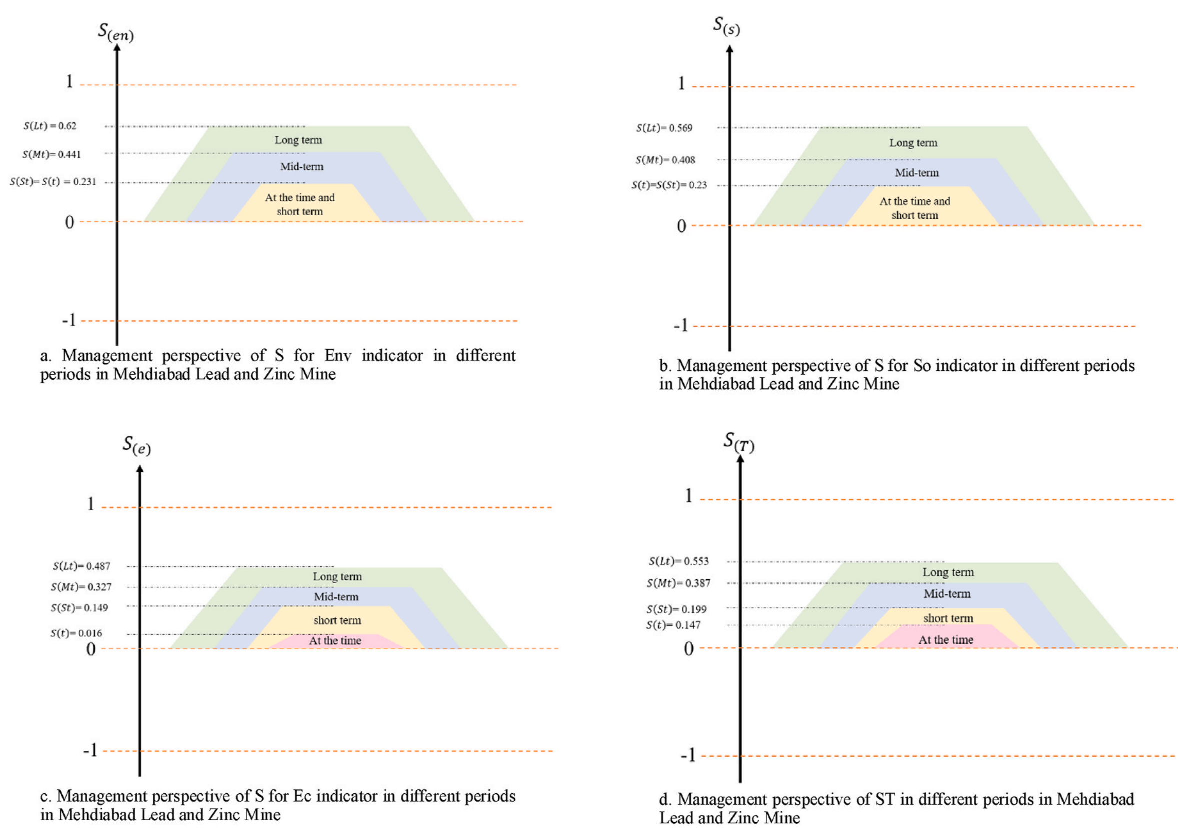
Based on above mentioned results the advantages and disadvantages of developed model are mention below:

Advantages.

- Specificity in Evaluation: Unlike many existing models that provide a generalized sustainability score, this model offers separate evaluations for each sustainability indicator (environmental, social, and economic). This allows for a more detailed understanding of sustainability levels in mining contexts.
- Integration of Strategic Management: this model combines strategic management principles with sustainability assessments, enabling short-term, medium-term, and long-term planning capabilities. This is a significant innovation that is not commonly found in other models.
- User-Friendly Implementation: The model is designed to be simple to implement, requiring only basic mathematical operations (addition, subtraction, multiplication, and division). This accessibility can attract a wider range of users, including those with limited technical expertise.
- Flexibility: This model can be used in all industries

Disadvantages.

- Complexity in Parameter Weighting: While the model provides detailed evaluations, the process of assigning weights to each index may introduce complexity that could be challenging for some users.
- Dependence on Expert Opinion: The model relies on expert evaluations to assess the impact of parameters on sustainability indicators. Depending on the expertise and perspectives of the evaluators, this could introduce subjectivity and variability in the results (all models based on expert opinion have the same challenges).



a. Management perspective of S for Env indicator in different periods in Mehdiabad Lead and Zinc Mine

b. Management perspective of S for So indicator in different periods in Mehdiabad Lead and Zinc Mine

c. Management perspective of S for Ec indicator in different periods in Mehdiabad Lead and Zinc Mine

d. Management perspective of ST in different periods in Mehdiabad Lead and Zinc Mine

Fig. 4. Mehdiabad lead and zinc Mine management perspective.

5. Evaluation of the proposed model in Mehdiabad Lead and zinc mine

Mehdiabad Lead and Zinc Mine in Iran is located 115 km southeast of Yazd City. In order to estimate the SD of this mine, the tables in Table A.1 to A.3 were given to the experts in this mine. Initially, they determined the IoC values with respect to the current condition of the mine, the types of mineral materials, and the social, economic, and environmental characteristics of the region. They then completed the columns of PS, MPPC(St), MPPC(Mt), and MPPC(Lt) in Tables 5–7, considering the abovementioned factors as well as management policies and priorities for controlling each parameter in the mine. After the scores were given based on the influence of parameters on SCs and MP (St), MP(Mt), and MP(Lt) were computed through equations (9)–(11), the two-dimensional SD assessment matrices for the three indicators were finalized (Table E.1 to E.3). Based on mtrixs output, and exsisting equations, the level of SD in this mine is as follow.

- Based on (equations (14)–(16)) and the tables related to the Env indicator in Table E.1, the S level of the Env indicator is 0.231
- Using (equations (19)–(21)) and the tables associated with the So indicator in Table E.2, the S level of the So indicator is 0.23
- Given (equations (24)–(26)) and the tables related to the Ec indicator in Table E.3, the S level of the Ec indicator is 0.016
- By considering the location of Mehdiabad Lead and Zinc Mine (Iran) and using (equation (29)), the S_T value for this mine is 0.147

5.1. Results of S assessment in Mehdiabad Lead and zinc mine

The results of the S assessment demonstrated that the S level of Mehdiabad Lead and Zinc Mine was positive with low sustainability (Table 10). In the current condition of the mine, the management strategies for Mehdiabad Lead and Zinc Mine in different periods are as follows.

- Short-term strategy: S_{Env} and S_{So} were in the acceptable ranges, and S_{Ec} was lower than the S levels of the other two indicators. It shows that in the St period, the mine owners should concentrate on upgrading the S_{Ec} of this mine. To this end, S(St) should be calculated for the mine by assuming that the controllable parameters of the Ec indicator are improved and the scores of the parameters in the Env and So indicators remain constant.
- Mid-term strategy: An evaluation should be carried out in the Mt period (10 years) by assuming that the parameters in all indicators are improved by 30 %. It is worth mentioning that the score of the 'resource depletion' parameter also increases if the extractive reserves remain stable in the mid-term.
- Long-term strategy: An evaluation should be performed in the Lt period (20 years) by assuming that the parameters in all indicators are improved by 50 %. Moreover, the scores given to the uncontrollable parameters in the social indicator, except for the 'resource depletion' parameter, are considered to be constant in different periods.

The scores were assigned to each parameter in each indicator considering the abovementioned strategies, and the results are provided in Table 12.

Given the scores of the parameters in different indicators and the conditions in the mine under study, the S value of each indicator and the S_T value were computed for the mine in different periods through the equations in Table 13.

Fig. 4 illustrates the management perspectives of S_{Env}, S_{So}, S_{Ec}, and S_T in different periods.

Based on the obtained results and the sustainability ranges provided in Tables 10 and it was found that the Mehdiabad Lead and Zinc Mine exhibited low levels of environmental (SEnv) and social (SSo) sustainability. At the time of investigation, the economic (SEc) sustainability level was extremely low, nearing zero, and the overall sustainability (ST) value was also low.

If efforts are made to improve the SEc level within the short-term (St) period, it is expected to increase from very low to low. However, even with this improvement in SEc, and assuming that the S levels of the other two indicators (SEnv and SSo) remain stable, the overall ST will show only a slight improvement, keeping the mine in the low sustainability range.

In the medium-term (Mt) period, if the proposed procedures and strategies are implemented to enhance all parameters, the overall ST for Mehdiabad Lead and Zinc Mine will reach a medium level, falling within a satisfactory sustainability range (as shown in Table 10).

Interviews with mine managers, along with the available evidence, indicate that extensive plans have been developed to improve sustainability. These plans include efforts in mining social responsibility, environmental preservation, and the creation of sustainable jobs and business opportunities, all aimed at raising the sustainability level of Mehdiabad Lead and Zinc Mine.

5.1.1. Model validation

For validation, the studied case was also evaluated using the Phillips model [12,13], and the results closely matched those from the extended model. While the Phillips model only assesses the overall sustainability level of a mine at a given point in time, it showed a sustainability score of 0.155 (indicating weak sustainability) for the Mehdiabad Lead and Zinc Mine. This value fell within the acceptable range of the extended model, confirming its accuracy. To further ensure the model's reliability, the results were cross-validated through field investigations at the Mehdiabad mine.

As expected, the model's results aligned with real-world conditions. Mehdiabad, the second-largest lead and zinc mine, is currently being equipped for mining operations in the near future and was officially opened in late 2023. From an economic standpoint, while the mine's economic sustainability is expected to be strong in the long term, its current sustainability level remains weak.

Since the mine has only recently begun operations, the natural surroundings have yet to undergo significant changes. As a result, the environmental sustainability level was rated as acceptable during the sustainability review. Socially, the mine has been undergoing stripping for several years, and its opening at the end of 2023 has created substantial job opportunities for the local population. This has led to significant social changes in the region, improving the mine's social sustainability.

5.1.2. Model uncertainty

The uncertainty of the model's results is an important factor that needs to be addressed, especially concerning the main findings. The model incorporates various parameters that can introduce uncertainty. For example, the estimation of ore reserves and grades has a certainty level of over 90 percent. However, fluctuations in the demand for mineral materials can also create uncertainty, as demand may deviate from expectations, impacting the sustainability assessment. Additionally, the model relies on expert evaluations to score the impact of parameters on sustainability components, which introduces another layer of uncertainty. The subjective nature of expert opinions can lead to variability, as different experts may have differing views on the significance of each parameter.

Moreover, the model's accuracy depends on the reliability of the input data and the assumptions made during the scoring process. If the data is flawed or if the assumptions do not hold in practice, the model's results may not accurately reflect the sustainability levels of the mining operation.

In summary, while the model has been validated through empirical case studies, it is crucial to acknowledge the uncertainties related to parameter estimation, expert evaluations, and data accuracy, as these factors can affect the reliability of the model's outcomes.

6. Conclusion

Previous models for evaluating SD primarily rely on a general indicator called the SD Indicator (S). However, these models fall short of providing detailed insights into the sustainability of each of the environmental, social, and economic dimensions. In other words, these models are unable to precisely demonstrate how much the S level is promoted within each indicator. For instance, in a given project, if there is a substantial increase in the S level of one indicator, it might lead to the mistaken conclusion that the project's overall SD is positive. Yet, the S levels for the other two indicators might be significantly negative. This kind of evaluation contradicts the very concept of SD, potentially resulting in false positive sustainability. Furthermore, many current SD assessment models tend to overlook recent advancements in technology and information, especially those introduced to the mining industry. Researchers often do not incorporate these modern technologies into their models, leading to outdated evaluations.

This study, conducted over more than eight years in the field of SD for mining, focuses on integrating key concepts related to both SD and mining. By utilizing recent technological advancements and information from diverse fields, including management and sustainability sciences, this research has developed a semi-quantitative model based on a two-dimensional matrix. One of the model's primary advantages is its simplicity, as it involves only basic mathematical operations—multiplication, addition, subtraction, and division. This simplicity makes the model highly accessible for users, particularly mine managers, allowing them to devise strategies to improve each sustainability indicator and its underlying parameters over the short, medium, and long terms. Moreover, the model provides a comprehensive view of SD by considering all relevant indicators across different timeframes. As a result, it delivers valuable insights about both the current and potential future conditions of a mine in a format that is easy for managers, stakeholders, and users to understand and act upon.

The study does have some limitations, primarily stemming from its reliance on expert evaluations, which can introduce subjectivity in scoring the impact of sustainability parameters. Since experts may have different perspectives on the importance of each parameter, this variability can affect the consistency and reliability of the results. Another potential limitation is the accuracy of the model's outputs, which depends on the quality of the input data. If the data used is flawed, or if the assumptions made during the scoring process do not hold up in practice, the model's findings may not accurately represent the true sustainability levels. Additionally, the model was specifically developed for the mining industry, with a particular focus on the geographic conditions of the studied case. This geographical specificity could limit the model's broader applicability to other industries or regions without significant adaptation, as the specific environmental and social factors in the studied area may heavily influence the results, making them less generalizable.

In terms of its scope, this study specifically focuses on sustainability assessment within the mining sector, aiming to provide a detailed evaluation of the environmental, social, and economic indicators. By incorporating strategic management principles, the model allows for planning and decision-making over short-, medium-, and long-term horizons to improve sustainability. The study builds upon existing models, such as those developed by Folchi and Phillips, by integrating new parameters and leveraging the latest technological advancements in SD. The model's design offers a semi-quantitative approach to evaluating sustainability in mining operations, which represents a significant innovation in the field. Additionally, the model's practical applicability was validated through an empirical case study, demonstrating its effectiveness in assessing real-world sustainability levels in a mining context. While the study presents a robust framework for sustainability assessment, it is important to recognize its limitations and the specific context in which it was developed to understand its implications and potential applications fully.

Compared to previous models, this new model is user-friendly and introduces substantial improvements in its concepts and parameters. Finally, with the addition of a strategic management component, the model can be regarded as revolutionary in the field of SD assessment, offering a more comprehensive and actionable approach to understanding and improving sustainability.

CRediT authorship contribution statement

Mahdi Pouresmaieli: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Ali Nouri Qarahasanlou:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition. **Mohammad Ataei:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing conflict of interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendices.

Table A.1
Scenarios designed for each parameter in the Env indicator

Number	Parameter	Scenarios		Score
1	Renewable energy	Fossil fuels and the national electricity network supply all the energy of the mine		8–10
		Renewable energies supply 1 %–40 % of the energy of the mine, and fossil fuels and the national electricity network provide the rest.		4–7
		Renewable energies supply more than 40 % of the energy of the mine.		0–3
2	IoT	Mine does not use any equipment related to the Internet of Things (IoT) to control pollution		8–10
		By using sensors and automation, the mine is relatively aware of the environmental issues and prevents people from emitting dangerous and tangible pollution.		4–7
		By using sensors and automation, the mine is thoroughly aware of all the incidents related to environmental issues and prevents the emission of pollution.		0–3
3	Ecological literacy	Mine owners have no ecological literacy and no knowledge about environmental preservation		8–10
		Mine owners have ecological literacy and are fully aware of environmental preservation but neglect environmental preservation.		4–7
		Mine owners have ecological literacy, are fully aware of environmental preservation, and attempt to avoid environmental destruction.		0–3
4	Phytoremediation	Mine owners do not know phytoremediation, and in the agricultural lands around the mining area, crops that absorb the heavy metals extracted from the mine are grown.		8–10
		Mine owners are relatively aware of phytoremediation, and in the agricultural lands around the mining area, it is avoided to grow crops that absorb the heavy metals extracted from the mine as much as possible.		4–7
		Mine owners are fully aware of phytoremediation, and people are highly informed about the ramifications of growing crops that absorb the heavy metals extracted from the mine, and growing these crops is strictly avoided.		0–3
5	Interference with surface waters	Interference with a pond or a river		8–10
		Interference with temporary water flows		4–7
		No interference with surface waters		0–3
6	Interference with underground waters	The presence of shallow and permeable underground water reservoirs		8–10
		The presence of deep and permeable underground water reservoirs		4–7
		The presence of deep and impenetrable underground water reservoirs		0–3
7	Emission of greenhouse gases and dust	Unrestricted emissions in the atmosphere		8–10
		Emission in licensed areas		4–7
		Very little emission in the mining area		0–3
8	Noise	The peak energy that is emitted in the air at a distance of 1 km from the mine	less than 141 dB	8–10
			less than 131 dB	4–7
			less than 121 dB	0–3
9	Ecological pollution	There is no tailing dam, and the pollution caused by gas, dust, sewage, and solid waste is not controlled in the mining site.		8–10
		Tailing dams have been built, but the pollution caused by gas, dust, sewage, and solid waste is not completely maintained in the mine site		4–7
		Tailing dams have been built, and the pollution caused by gas, dust, sewage, and solid waste is completely controlled and maintained in the mine site		0–3
10	Destruction of vegetation coverage	The mine occupies the area; the vegetation coverage has been destroyed, and it is not easy to restore the vegetation coverage. The number of springs has been reduced, and the exploited wells have almost dried up in the mine site; the mining site was suitable for agriculture, and the land used to be fertile before mining, but now it is destroyed by mining activities.		8–10
		The mine occupies the area; the vegetation coverage has been destroyed, and it is difficult to restore the vegetation coverage; the level of underground water has decreased; the number of springs and the water level of wells used in the mining site have been reduced drastically; the area used to be a forest before mining, but now the landscape in the mining site has moderately changed.		4–7
		The mine occupies the area; the vegetation coverage in the area has been destroyed, but it is easy to restore the vegetation coverage; the level of underground water and the number of springs have not decreased significantly, and the number of dried wells has not remarkably increased in the mining area; the area used to be industrial before mining.		0–3
11	Acid Mine Drainage (AMD)	The mine produces acidic water, and its distance from the city is less than 35 km		8–10
		The mine produces acidic water, and its distance from the city is more than 35 km		4–7
		The mine does not produce acidic water		0–3
12	Creation of suitable habitats to preserve animal species in the region	The mine does not have any plans to preserve plant and animal species		8–10
		Under the pressure of the relevant institutions, the mine periodically implements programs designed for the preservation of plant and animal species in the mining area.		4–7
		The mine has detailed and continuous plans to preserve plant and animal species		0–3
13	Geological conditions	The presence of developed active faults in soft or hard rocks		8–10
		The presence of relatively developed faults in soft or hard rocks		4–7
		The absence of active faults		0–3
14	Hydrological conditions	Complicated conditions		8–10
		Suitable conditions		4–7
		Simple conditions		0–3

(*continued on next page*)

Table A.1 (*continued*)

Number	Parameter	Scenarios	Score
15	Mining-related contractors	Mining contractors rarely pay attention to environmental issues and merely consider economic issues while dealing with mining activities	8–10
		Mining contractors sometimes assess environmental problems raised by mining.	4–7
		Mining contractors substantially attend to environmental issues while dealing with mining activities	0–3
16	Possibility of failure of the tailing dam	The safety factor is less than 1	8–10
		The safety factor is between 1 and 1.5	4–7
		The safety factor is more than 1.5	0–3
17	Reclamation	Through the restoration plan, vegetation development is low, and the coverage scale is less than 20 %.	8–10
		Through the restoration plan, vegetation development is appropriate, and the coverage scale is between 20 % and 60 %.	4–7
		Through the restoration plan, vegetation development is satisfactory, and the coverage scale is more than 60 %.	0–3
18	Change of land use	The land used to be a park or a preserved area	9–10
		The land used to be a residential area	6–8
		The land used to be an agricultural area	3–5
		The land used to be an industrial area	0–2
19	Fly-rock	There is no explosion	8–10
		There are explosions, but no cleaning methods are used after explosions	4–7
		There are explosions, and some cleaning methods are used after explosions	0–3
20	Tailing dam leakage	Heavy metals cover more than 66 % of soil elements around the mine	8–10
		Heavy metals cover between 33 % and 66 % of soil elements around the mine	4–7
		Heavy metals cover less than 33 % of the soil elements around the mine	0–3

Table A.2
Scenarios designed for each parameter in So indicator

Number	Parameter	Scenarios	Score
1	Renewable energy	The use of renewable energy has led to the occupation of agricultural lands, which reduces employment in the mining area	8–10
		The use of renewable energy has created employment and led to the migration of the specialized workforce	4–7
		The use of renewable energy has increased the technological knowledge of people in the mining area; indigenous people in the mining area have acquired new expertise, which has boosted their employment.	0–3
2	IoT	The mine does not use IoT to examine workers' physical health and safety	8–10
		The mine uses IoT to control either the health or safety of workers in the mining site	4–7
		The mine uses IoT to control both the physical health and safety of workers in the mine site	0–3
3	Ecological Literacy	The mine provides periodic and continuous training on ecological literacy for workers, and all workers are highly inclined to observe the trained principles	8–10
		The mine provides periodic and continuous training on ecological literacy for workers, but workers are not inclined to observe the trained principles	4–7
		No training on ecological literacy is provided for workers	0–3
4	Effect of mining machinery on traffic and road infrastructure of the region	200 % increase in traffic	8–10
		100 % increase in traffic	4–7
		Low impact on traffic	0–3
5	Training workforce	No training is provided for workers	8–10
		Cross-sectional training is provided for workers	4–7
		Periodic training is provided for workers.	0–3
6	Safety	The road slope is more than 12 %, and the wall slope is more than the standard level, considering the stone type	8–10
		Semi-automated machines are used; the slope is between 8 % and 12 %; the road width is standard; and the wall slope is standard considering the stone type	4–7
		Fully automated machines are used; the slope is less than 8 %; the road width is less than the standard level; and the wall slope is less than the standard level considering the stone type	0–3
7	Use of skilled workforce	The workforce has no knowledge or work experience	8–10
		The workforce has a good deal of work experience	4–7
		The workforce has a lot of experience and sufficient knowledge of mining (education).	0–3
8	Child labor avoidance	Children work in the mine, and mine owners take no action to prevent it	8–10
		Children work in the mine in a limited way, and when mine owners become aware of it, they take action to prevent it	4–7
		There are no workers under legal age in the mine	0–3
9	Economic prosperity and employment in the mining region	Mining has reduced employment in the mining area	8–10
		Mining has increased employment in the mining area	4–7
		Mining has changed employment in the mining area, and employment has increased sharply	0–3
10	Respecting the characteristics of indigenous people in the mining area	The indigenous people have no interest in mining and prefer traditional jobs to mining jobs.	8–10
		The Indigenous people are interested in mining jobs only under specific conditions	4–7
		The indigenous people welcome mining jobs with open arms	0–3
11	Creating environmental welfare for workers	The mine does not care about environmental welfare and environmental sanitation	8–10
		The mine provides relatively suitable environmental welfare for workers and pays special attention to environmental sanitation	4–7
		The mine provides suitable environmental welfare for workers and pays special attention to environmental sanitation and welfare problems	0–3

(*continued on next page*)

Table A.2 (*continued*)

Number	Parameter	Scenarios	Score
12	Attention to issues related to the health of workers and mine employees	Mining has caused severe and incurable health problems for workers.	8–10
		Mining has caused severe but curable health problems for workers.	4–7
		Mining has not raised any health problems for workers.	0–3
13	Resource depletion	The mine life is less than 5 years	8–10
		The mine life is between 5 and 20 years	4–7
		The mine life is more than 20 years	0–3
14	Preservation of ancient heritage	The mine is located in a historical area, and historical objects are sometimes found in the mine during mining.	8–10
		The mine is located around a historical area, but no historical objects are found in the mine during mining.	4–7
		The mine is not located in a historical area, and no historical objects are found during mining.	0–3
15	Mining-related contractors	Mining contractors rarely pay attention to social issues and only consider economic issues when dealing with mining.	8–10
		From time to time, contractors assess the social issues raised by mining.	4–7
		Mining contractors pay special attention to social issues when dealing with mining.	0–3
16	Employment, income, and life expectancy	Employment, income, and life expectancy have decreased since the start of mining operations.	8–10
		Employment, income, and life expectancy have not changed since the start of mining operations.	4–7
		Employment, income, and life expectancy have increased since the start of mining operations	0–3
17	Importance of the region	The mining site is on the outskirts of the city, has a great impact on the traffic of the main roads, and has tourist areas or includes large projects.	8–10
		The mining site is close to the main roads of the city and is a tourist area.	4–7
		The mining site is located in the country or the mountains and is far from important transit roads and tourist areas.	0–3
18	Change of land use	The mining area used to be a tourist area and provided high employment opportunities for the indigenous people	8–10
		The mining region used to be an agricultural area, and part of the livelihood of the indigenous people in the region depended on it	4–7
		The mining area used to be a barren area and did not affect the employment of the indigenous people.	0–3

Table A.3
Scenarios designed for each parameter in the Ec indicator

Number	Parameter	Scenarios	Score
1	Renewable energy	The use of renewable energies does not affect the economy of the mine	8–10
		The use of renewable energies has created a circular business in the mine, or the mine earns money by selling surplus energy.	4–7
		The use of renewable energies has created a circular business in the mine; the mine earns money by selling surplus energy; and the use of renewable energies has increased the productivity of the mine and reduced the limit grade in the mine.	0–3
2	IoT	The mine does not use IoT for economic purposes	8–10
		The use of IoT has boosted the productivity of the mine	4–7
		The use of IoT has increased productivity, reduced the limit grade, and raised the mine life	0–3
3	Effect of mining machinery on traffic and road infrastructure of the region	Traffic has increased by more than 200 % and has reduced the economic prosperity of the mining area	8–10
		Traffic has increased by more than 100 % and has reduced the economic prosperity of the mining area	4–7
		Traffic has not impacted the economic prosperity of the mining area	0–3
4	Economic prosperity and employment of the mining area	Mining has decreased the economic prosperity of the mining area.	8–10
		Mining has increased the economic prosperity of the mining area.	4–7
		Mining has transformed the economic prosperity of the mining area, and economic prosperity has sharply increased.	0–3
5	Equipment (drilling, loading, and transporting equipment)	The mining machinery is old, and its repair and maintenance costs are high.	8–10
		The mining machinery is new, and its repair and maintenance costs are high.	4–7
		The mining machinery is up-to-date and based on the latest technology in the world.	0–3
6	Resource depletion	The resources are strategic and have a great impact on the economy of the area	8–10
		The resources are strategic but do not have a great impact on the economy of the area, or they are not strategic but have a great impact on the economy of the area.	4–7
		The resources are not strategic and have no impact on the economy of the area	0–3
7	Employment, income, and life expectancy	The indigenous people have lost their income due to mining	8–10
		The income of indigenous people has decreased due to mining	4–7
		The income of indigenous people has increased due to mining	0–3
8	Prices of Products	The prices of products have remarkably fluctuated over the past years.	8–10
		The prices of products have slightly fluctuated over the past years or have had a declining trend.	4–7
		The prices of products have remained stable or have had a predictable growth pattern over the past years	0–3
9	Government	The government does not support mining at all and has set many taxes for this sector.	8–10
		The government has offered several support packages for this sector.	4–7
		The government fully supports the mining sector and has set small taxes for this sector	0–3
10	Discount rate	The discount rate is more than 15 %	8–10
		The discount rate is between 8 % and 15 %	4–7
		The discount rate is less than 8 %	0–3
11	Profitability of mine	The mine has not made the expected profitability and is losing money.	8–10
		The mine has not made the expected profitability and only covers the costs of mining, repair and maintenance, transportation, and labor.	4–7
		The mine has made the expected profitability	0–3
12	Operating costs	Operating costs are more than 7.5 dollars per ton of ore	8–10

(*continued on next page*)

Table A.3 (*continued*)

Number	Parameter	Scenarios	Score
		Operating costs are between 6 and 7.5 dollars per ton of ore	4–7
		Operating costs are less than 6 dollars per ton of ore	0–3
13	Uncertainty (ore reserve and grade)	Certainty in ore reserve and grade estimation is less than 75 %	8–10
		Certainty in ore reserve and grade estimation is between 75 % and 90 %	4–7
		Certainty in ore reserve and grade estimation is more than 90 %	0–3
14	Demand	Demand for mineral materials from the mine is less than expected	8–10
		Demand for mineral materials from the mine is as expected.	4–7
		Demand for mineral materials from the mine is more than expected.	0–3
15	Proportionality of workers' and employees' salaries to the difficulty of labor in the mine	Workers are paid less than the value of their labor, and the mine prioritizes income over workers' rights.	8–10
		Workers are paid less than the value of their labor, given the difficulty of working in the mine.	4–7
		Workers' salaries are proportionate to or more than their labor	0–3
16	Change of land use	The mining area used to be a tourist area, and the indigenous people earned much money	8–10
		The mining area used to be an agricultural area, and part of the economy and livelihood of the indigenous people in the area depended on it.	4–7
		The mining area used to be a barren area and did not affect the economy of the indigenous people.	0–3

Table B.1
Two-dimensional SD assessment matrix of Env indicator completed by experts

No	Parameter	Human health and safety	Social relationship	Water quality	Air quality	Use of territory	Flora and fauna	Above ground	Underground	Landscape	Noise	Economy	Soil quality
1	Renewable energy	4	2	3	5	4	3	4	1	2	0	4	2
2	IoT	5	1	4	4	0	1	4	4	2	0	4	4
3	Ecological literacy	5	4	3	3	3	5	4	2	1	3	3	4
4	Phytoremediation	3	1	4	2	1	5	3	1	3	0	1	5
5	Interference with surface waters	4	3	5	1	3	3	4	2	3	1	3	3
6	Interference with underground waters	4	3	5	1	2	2	2	4	2	1	3	3
7	Emission of greenhouse gases and dust	4	3	3	5	2	3	2	1	3	1	3	2
8	Noise	4	4	0	1	2	1	2	1	2	4	2	1
9	Ecological pollution	5	4	4	4	3	4	3	2	3	1	4	3
10	Destruction of vegetation coverage	3	3	3	3	2	4	4	1	4	2	3	3
11	Acid Mine Drainage (AMD)	4	3	5	2	3	4	4	3	3	0	3	4
12	Construction of suitable habitats to preserve animal species in the region	4	2	2	3	4	5	3	1	3	0	1	3
13	Geological conditions	2	1	2	1	3	2	3	3	3	0	3	2
14	Hydrological conditions	2	1	3	2	3	2	3	3	2	0	3	2
15	Mining contractors	4	3	3	2	2	2	2	2	3	3	4	3
16	Possibility of failure of tailing dam	5	4	4	2	4	4	4	2	4	0	4	3
17	Reclamation	4	4	3	3	3	4	3	1	4	2	3	3
18	Change of land use	2	2	3	2	3	3	3	3	4	2	3	3
19	Fly-rock	4	3	1	1	2	1	2	1	1	2	1	1
20	Tailing dam leakage	4	3	4	2	3	4	4	2	3	0	3	3
Total column		76	54	64	49	52	62	63	40	55	22	58	57

Table B.2
Two-dimensional SD assessment matrix of So indicator completed by experts

No	Parameter	Human health and safety	Social relationship	Water quality	Air quality	Use of territory	Flora and fauna	Above ground	Underground	Landscape	Noise	Economy	Soil quality
1	Renewable energy	4	2	3	5	4	3	4	1	2	0	4	2
2	IoT	5	1	4	4	0	1	4	4	2	0	4	4
3	Ecological literacy	5	4	3	3	3	5	4	2	1	3	3	4
4	Effect of mining machinery on traffic and road infrastructure of the region	3	4	1	3	2	3	2	1	2	4	3	2
5	Training the workforce	4	3	2	2	2	1	1	2	2	2	4	1
6	Safety	5	5	2	2	2	2	2	3	2	3	4	1
7	Use of skilled workforce	5	4	3	3	1	3	1	1	2	3	4	1
8	Child labor avoidance	5	5	4	4	3	4	3	3	3	3	4	2
9	Economic prosperity and employment in the mining region	4	4	0	0	2	1	3	0	3	1	5	2
10	Respecting the characteristics of indigenous people in the mining region	2	4	2	1	3	2	2	2	3	2	4	2
11	Creating environmental welfare for workers	5	5	1	0	2	0	2	1	2	0	3	1
12	Attention to issues related to the health of workers and mine employees	5	4	2	2	1	1	1	2	0	0	3	0
13	Resource depletion	2	3	2	2	3	2	2	2	3	1	4	2
14	Preservation of ancient heritage	0	2	0	0	4	1	2	2	2	0	2	1
15	Mining-related contractors	4	3	3	2	2	2	2	2	3	3	4	3
16	Employment, income, and life expectancy	4	5	1	1	1	1	0	0	0	1	4	1
17	Importance of the region	2	3	2	2	4	3	3	3	3	2	3	3
18	Change of land use	2	2	3	2	3	3	3	3	4	2	3	3
Total column		66	63	38	38	42	38	41	34	39	30	65	35

Table B.3
Two-dimensional SD assessment matrix of Ec indicator completed by experts

No	Parameter	Human health and safety	Social relationship	Water quality	Air quality	Use of territory	Flora and fauna	Above ground	Underground	Landscape	Noise	Economy	Soil quality
1	Renewable energy	4	2	3	5	4	3	4	1	2	0	4	2
2	IoT	5	1	4	4	0	1	4	4	2	0	4	4
3	Effect of mining machinery on traffic and road infrastructure of the region	3	4	1	3	2	3	2	1	2	4	3	2
4	Economic prosperity and employment in the mining region	4	4	0	0	2	1	3	0	3	1	5	2
5	Equipment (drilling, loading, and transporting equipment)	4	1	1	3	1	1	3	2	1	4	5	1
6	Resource depletion	2	3	2	2	3	2	2	2	3	1	4	2
7	Employment, income, and life expectancy	4	5	1	1	1	1	0	0	0	1	4	1
8	Prices of products	2	1	0	0	2	0	0	0	0	0	5	0
9	Government	4	4	2	2	4	2	2	1	3	2	4	2
10	Discount rate	1	0	0	2	0	1	0	0	1	0	5	0
11	Profitability of mine	3	2	0	0	3	0	1	0	0	2	5	0
12	Operating costs	2	1	1	0	0	1	1	0	0	2	5	1
13	Uncertainty (ore reserve and grade)	0	1	1	1	2	1	1	2	1	0	4	0
14	Demand	2	2	2	2	3	2	2	2	2	2	5	2
15	Proportionality of workers' and employees' salaries to the difficulty of working in the mine	3	4	0	0	1	0	0	0	2	0	4	0
16	Change of land use	2	2	3	2	3	3	3	3	4	2	3	3
Total column		45	37	21	27	31	22	28	18	26	21	69	22

Table C.1
Score ranges and their description in the IoC column

Score range	Description
9–10	There is very high importance on controlling the parameter
7–8	The high importance of controlling the parameter
5–6	Neutral (not high nor low) importance of controlling the parameter
3–4	There is little importance in controlling the parameter
0–2	There is very little importance in controlling the parameter

Table D.1
Score ranges and their description in the MPPC column

Score range	Description
9–10	Controlling the parameters based on management policies prevalent in the mine is considered urgent during the study period.
7–8	Controlling the parameters based on the management policies prevalent in the mine is not one of the top priorities but is considered very important during the study period.
5–6	Controlling the parameters based on the management policies prevalent in the mine is considered important during the study period.
3–4	Controlling the parameters based on the management policies prevalent in the mine is important during the study period.
0–2	Controlling the parameters based on the management policies prevalent in the mine is considered unimportant during the study period.

Table E.1
The final version of the two-dimensional SD assessment matrix of the Env indicator for Mehdiabad Lead and Zinc Mine

No	Parameter	The score is given to the desired parameter according to the available scenarios (PS)	Sustainable Components (SC)												The possibility of controlling the desired parameter (PoC)	The importance of controlling or improving the desired parameter according to the situation of the case study (IoC)	The policy of managers to control the desired parameter of case study in the short term (MPPC(St))	The policy of managers to control the desired parameter of case study in the mid-term (MPPC(Mt))	The policy of managers to control the desired parameter of case study in the long term (MPPC(Lt))	The management priority is to control the desired parameter of the case study in the short term (MP(St))	The management priority to control the desired parameter of the case study in the mid-term (MP(Mt))	The management priority is to control the desired parameter of the case study in the long term (MP(Lt))
			Human health and safety	Social relationship	Water quality	Air quality	Use of territory	Flora and fauna	Above ground	Under ground	Landscape	Noise	Economy	Soil quality								
1	Renewable energy	10	5.26	3.70	4.69	10.20	7.69	4.84	6.35	2.50	3.64	0.00	6.90	3.51	1	7	7	7	7	490	490	490
2	IoT	10	6.58	1.85	6.25	8.16	0.00	1.61	6.35	10.00	3.64	0.00	6.90	7.02	1	6	8	8	9	480	480	540
3	Ecological literacy	2	1.32	1.48	0.94	1.22	1.15	1.61	1.27	1.00	0.36	2.73	1.03	1.40	1	3	2	2	3	12	12	18
4	Phytoremediation	6	2.37	1.11	3.75	2.45	1.15	4.84	2.86	1.50	3.27	0.00	1.03	5.26	1	5	5	5	6	150	150	180
5	Interference with surface waters	6	3.16	3.33	4.69	1.22	3.46	2.90	3.81	3.00	3.27	2.73	3.10	3.16	1	5	5	5	6	150	150	180
6	Interference with underground waters	6	3.16	3.33	4.69	1.22	2.31	1.94	1.90	6.00	2.18	2.73	3.10	3.16	1	6	6	6	7	216	216	252
7	Emission of greenhouse gases and dust	3	1.58	1.67	1.41	3.06	1.15	1.45	0.95	0.75	1.64	1.36	1.55	1.05	1	1	2	2	4	6	6	12
8	Noise	2	1.05	1.48	0.00	0.41	0.77	0.32	0.63	0.50	0.73	3.64	0.69	0.35	1	1	1	2	2	2	4	4
9	Ecological pollution	2	1.32	1.48	1.25	1.63	1.15	1.29	0.95	1.00	1.09	0.91	1.38	1.05	1	2	2	3	3	8	12	12
10	Destruction of vegetation coverage	3	1.18	1.67	1.41	1.84	1.15	1.94	1.90	0.75	2.18	2.73	1.55	1.58	1	2	2	2	2	12	12	12
11	Acid Mine Drainage (AMD)	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1	0	0	0	0	0	0	0
12	Construction of suitable habitats to preserve animal species in the region	2	1.05	0.74	0.63	1.22	1.54	1.61	0.95	0.50	1.09	0.00	0.34	1.05	1	8	6	6	8	96	96	128
13	Geological conditions	3	0.79	0.56	0.94	0.61	1.73	0.97	1.43	2.25	1.64	0.00	1.55	1.05	0	-	-	-	-	-	-	-
14	Hydrological conditions	3	0.79	0.56	1.41	1.22	1.73	0.97	1.43	2.25	1.09	0.00	1.55	1.05	0	-	-	-	-	-	-	-
15	Mining contractors	3	1.58	1.67	1.41	1.22	1.15	0.97	0.95	1.50	1.64	4.09	2.07	1.58	1	3	3	4	5	27	36	45
16	Possibility of failure of tailing dam	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1	0	0	0	0	0	0	0
17	Reclamation	5	2.63	3.70	2.34	3.06	2.88	3.23	2.38	1.25	3.64	4.55	2.59	2.63	1	5	5	7	7	125	125	175
18	Change of land use	9	2.37	3.33	4.22	3.67	5.19	4.35	4.29	6.75	6.55	8.18	4.66	4.74	0	-	-	-	-	-	-	-
19	Fly-rock	4	2.11	2.22	0.63	0.82	1.54	0.65	1.27	1.00	0.73	3.64	0.69	0.70	1	4	3	3	4	48	48	64
20	Tailing dam leakage	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1	0	0	0	0	0	0	0
Total column			38.29	33.89	40.63	43.27	35.77	35.48	39.68	42.50	38.36	37.27	40.69	40.35								

Table E.2
The final version of the two-dimensional SD assessment matrix of So indicator for Mehdiabad Lead and Zinc Mine

No	Parameter	The score is given to the desired parameter according to the available scenarios (PS)	Sustainable Components (SC)												The possibility of controlling the desired parameter (PoC)	The importance of controlling or improving the desired parameter according to the situation of the case study (IoC)	The policy of managers to control the desired parameter of case study in the short term (MPPC(St))	The policy of managers to control the desired parameter of case study in the mid-term (MPPC(Mt))	The policy of managers to control the desired parameter of case study in the long term (MPPC(Lt))	The management priority is to control the desired parameter of the case study in the short term (MP(St))	The management priority is to control the desired parameter of the case study in the mid-term (MP(Mt))	The management priority is to control the desired parameter of the case study in the long term (MP(Lt))
			Human health and safety	Social relationship	Water quality	Air quality	Use of territory	Flora and fauna	Above ground	Underground	Landscape	Noise	Economy	Soil quality								
1	Renewable energy	10	6.06	3.17	7.89	13.16	9.52	7.89	9.76	2.94	5.13	0.00	6.15	5.71	1	7	7	7	8	490	490	560
2	IoT	10	7.58	1.59	10.53	10.53	0.00	2.63	9.76	11.76	5.13	0.00	6.15	11.43	1	8	8	8	8	640	640	640
3	Ecological literacy	3	2.27	1.90	2.37	2.37	2.14	3.95	2.93	1.76	0.77	3.00	1.38	3.43	1	2	3	4	4	18	24	24
4	Effect of mining machinery on traffic and road infrastructure of the region	3	1.36	1.90	0.79	2.37	1.43	2.37	1.46	0.88	1.54	4.00	1.38	1.71	1	3	3	4	5	27	36	45
5	Training the workforce	2	1.21	0.95	1.05	1.05	0.95	0.53	0.49	1.18	1.03	1.33	1.23	0.57	1	2	4	4	4	16	16	16
6	Safety	5	3.79	3.97	2.63	2.63	2.38	2.63	2.44	4.41	2.56	5.00	3.08	1.43	1	5	5	5	6	125	125	150
7	Use of skilled workforce	3	2.27	1.90	2.37	2.37	0.71	2.37	0.73	0.88	1.54	3.00	1.85	0.86	1	3	6	7	8	54	63	72
8	Child labor avoidance	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1	0	0	0	0	0	0	0
9	Economic prosperity and employment in the mining region	2	1.21	1.27	0.00	0.00	0.95	0.53	1.46	0.00	1.54	0.67	1.54	1.14	1	2	2	4	6	8	16	24
10	Respecting the characteristics of indigenous people in the mining region	3	0.91	1.90	1.58	0.79	2.14	1.58	1.46	1.76	2.31	2.00	1.85	1.71	1	1	3	5	5	9	15	15
11	Creating environmental welfare for workers	3	2.27	2.38	0.79	0.00	1.43	0.00	1.46	0.88	1.54	0.00	1.38	0.86	1	2	4	7	8	24	42	48
12	Attention to issues related to the health of workers and mine employees	3	2.27	1.90	1.58	1.58	0.71	0.79	0.73	1.76	0.00	0.00	1.38	0.00	1	3	5	5	8	45	45	72
13	Resource depletion	3	0.91	1.43	1.58	1.58	2.14	1.58	1.46	1.76	2.31	1.00	1.85	1.71	0	-	-	-	-	-	-	-
14	Preservation of ancient heritage	3	0.00	0.95	0.00	0.00	2.86	0.79	1.46	1.76	1.54	0.00	0.92	0.86	1	3	3	3	3	27	27	27
15	Mining-related contractors	4	2.42	1.90	3.16	2.11	1.90	2.11	1.95	2.35	3.08	4.00	2.46	3.43	1	5	3	3	4	60	60	80
16	Employment, income, and life expectancy	4	2.42	3.17	1.05	1.05	0.95	1.05	0.00	0.00	0.00	1.33	2.46	1.14	1	5	2	3	5	40	60	100
17	Importance of the region	5	1.52	2.38	2.63	2.63	4.76	3.95	3.66	4.41	3.85	3.33	2.31	4.29	0	-	-	-	-	-	-	-
18	Change of land use	3	0.91	0.95	2.37	1.58	2.14	2.37	2.20	2.65	3.08	2.00	1.38	2.57	0	-	-	-	-	-	-	-
Total column			39.39	33.65	42.37	45.79	37.14	37.11	43.41	41.18	36.92	30.67	38.77	42.86								

Table E.3
The final version of the two-dimensional SD assessment matrix of Ec indicator for Mehdiabad Lead and Zinc Mine

No	Parameter	The score is given to the desired parameter according to the available scenarios (PS)	Sustainable Components (SC)												The possibility of controlling the desired parameter (PoC)	The importance of controlling or improving the desired parameter according to the situation of the case study (IoC)	The policy of managers to control the desired parameter of case study in the short term (MPPC (St))	The policy of managers to control the desired parameter of case study in the mid-term (MPPC (Mt))	The policy of managers to control the desired parameter of case study in the long term (MPPC (Lt))	The management priority is to control the desired parameter of the case study in the short term (MP(St))	The management priority is to control the desired parameter of the case study in the mid-term (MP (Mt))	The management priority is to control the desired parameter of the case study in the long term (MP(Lt))
			Human health and safety	Social relationship	Water quality	Air quality	Use of territory	Flora and fauna	Above ground	Underground	Landscape	Noise	Economy	Soil quality								
1	Renewable energy	10	8.89	5.41	14.29	18.52	12.90	13.64	14.29	5.56	7.69	0.00	5.80	9.09	1	7	5	7	7	350	490	490
2	IoT	10	11.11	2.70	19.05	14.81	0.00	4.55	14.29	22.22	7.69	0.00	5.80	18.18	1	8	7	8	8	560	640	640
3	Effect of mining machinery on traffic and road infrastructure of the region	3	2.67	4.32	1.90	4.44	2.58	5.45	2.86	2.22	3.08	7.62	1.74	3.64	1	3	3	3	5	36	36	60
4	Economic prosperity and employment in the mining region	0	2.67	3.24	0.00	0.00	1.94	1.36	3.21	0.00	3.46	1.43	2.17	2.73	1	5	3	4	7	45	60	105
5	Equipment (drilling, loading, and transporting equipment)	8	4.44	1.35	2.38	5.56	1.61	2.27	5.36	5.56	1.92	9.52	3.62	2.27	1	5	3	3	5	75	75	125
6	Resource depletion	10	3.56	6.49	7.62	5.93	7.74	7.27	5.71	8.89	9.23	3.81	4.64	7.27	0	–	–	–	–	–	–	–
7	Employment, income, and life expectancy	0	2.67	4.05	1.43	1.11	0.97	1.36	0.00	0.00	0.00	1.43	1.74	1.36	1	4	3	5	6	36	60	72
8	Prices of products	8	1.78	1.08	0.00	0.00	2.58	0.00	0.00	0.00	0.00	0.00	2.90	0.00	0	–	–	–	–	–	–	–
9	Government	5	2.67	3.24	2.86	2.22	3.87	2.73	2.14	1.67	3.46	2.86	1.74	2.73	0	–	–	–	–	–	–	–
10	Discount rate	10	1.78	0.00	0.00	5.93	0.00	3.64	0.00	0.00	3.08	0.00	5.80	0.00	0	–	–	–	–	–	–	–
11	Profitability of mine	0	2.00	1.62	0.00	0.00	2.90	0.00	1.07	0.00	0.00	2.86	2.17	0.00	1	7	1	2	3	21	42	63
12	Operating costs	4	3.56	2.16	3.81	0.00	0.00	3.64	2.86	0.00	0.00	7.62	5.80	3.64	1	8	8	9	9	512	512	512
13	Uncertainty (ore reserve and grade)	4	0.00	0.81	1.43	1.11	1.94	1.36	1.07	3.33	1.15	0.00	1.74	0.00	1	3	3	3	3	27	27	27
14	Demand	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	–	–	–	–	–	–	–
15	Proportionality of workers' and employees' salaries to the difficulty of working in the mine	9	4.00	6.49	0.00	0.00	1.94	0.00	0.00	0.00	4.62	0.00	3.48	0.00	1	7	5	6	7	210	252	294
16	Change of land use	0	0.44	0.54	1.43	0.74	0.97	1.36	1.07	1.67	1.54	0.95	0.43	1.36	0	–	–	–	–	–	–	–
Total column			52.22	43.51	56.19	60.37	41.94	48.64	53.93	51.11	46.92	38.10	49.57	52.27								

Data availability

The data that has been used is confidential.

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