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A New Comprehensive Model for Integrating Environmental, Economic, and Social Performance of Deep and Large-scale Open-Pit Copper Mines

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ABSTRACT

Deep and large-scale (D&LS) open-pit mines pose various environmental, social, and economic impacts on the mining projects' stakeholders and local, regional, national, and international communities. Identifying these impacts and having a comprehensive model to assess these impacts altogether is critical to achieving sustainable development (SD) goals. This study develops a robust sustainability assessment model for D&LS open-pit mining projects. The model comprehensively considers 99 impact factors across environmental, social, and economic dimensions. The sustainability score is calculated using the Z-FDAHP technique to reduce the bias and uncertainty of experts' judgments. Then, the scenario-based technique is used to apply the stakeholders' perspective to the model. The model is applied to Sungun Copper Mine (SCM) in northwest Iran for verification. Results show SCM's sustainability performance is highly sensitive to index weightings. The highest score was achieved with sole social prioritization (scenario 8 with a sustainability score of 6.364 out of 10), highlighting the critical role of community impacts. Environmental or economic focus alone (scenarios 2 and 5) was not very sustainable, with scores of 3.326 and 5.298 respectively. Scores of 5.543, 5.330, and 5.117 for sustainability can be achieved by optimizing all three SD aspects with a long-term, stakeholder-centered approach (scenarios 9, 4, and 6). The proposed sustainability assessment model exhibits robustness through its comprehensive set of 99 environmental, social, and economic indicators; its ability to customize indicator weights under different stakeholder-perspective scenarios; and validation of the quantitative scoring approach through an empirical case study, while continuous improvement would further reinforce its robustness over time.

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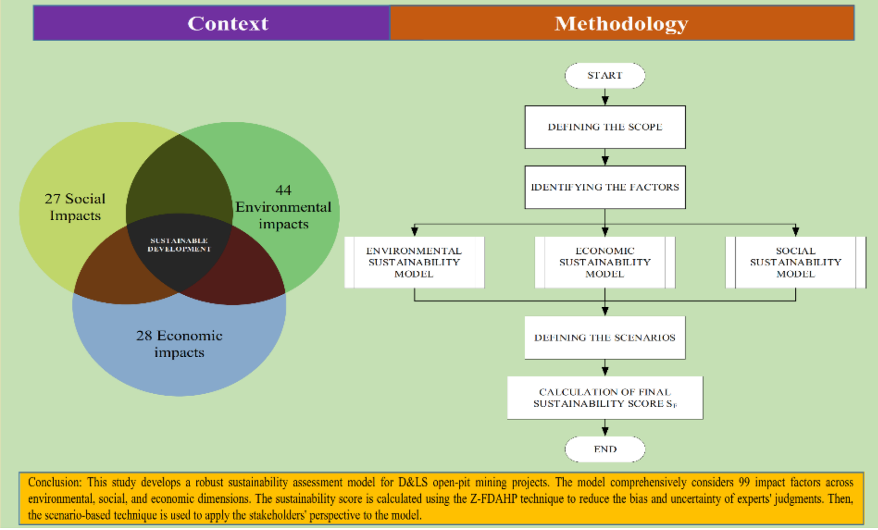
Graphical Abstract



Conclusion: This study develops a robust sustainability assessment model for D&LS open-pit mining projects. The model comprehensively considers 99 impact factors across environmental, social, and economic dimensions. The sustainability score is calculated using the Z-FDAHP technique to reduce the bias and uncertainty of experts' judgments. Then, the scenario-based technique is used to apply the stakeholders' perspective to the model.

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1. INTRODUCTION

Copper mining provides a resource that is important for many industrial uses. Reasons for rising copper demand include a growing world population, greater economic activity, and increased manufacturing of copper-containing products like power cables, electronics, plumbing, and building materials. Along with the depletion of high-quality, easily accessible copper sources, large-scale mining of lower-grade and deeper copper deposits has become necessary due to this increased demand. However, copper mining, like many other metals and minerals mining, impacts environmental, economic, and social aspects requiring management for sustainable development. Deep and Large-Scale (D&LS) open-pit mines present unique sustainability challenges due to their large scale, high resource throughput, emissions, water usage, land use impacts, and potential effects on communities and ecosystems. These complex projects require thorough, sophisticated analyses to balance mining needs with environmental and social responsibility. However, with careful planning and stakeholder involvement, such operations can help meet increasing copper demand in an environmentally and socially responsible manner while minimizing negative impacts. Numerous scholars have researched the environmental, economic, and social impacts of mining activities.

Vizayakumar and Mohapatra (1) addressed the environmental impacts of coal mining activity. Coal is the primary source of energy in India, but environmental pollution in agricultural areas is very severe. Rybicka (2) examined the environmental impacts of mines in Poland and noted an increasing concentration of pollutants, especially heavy metals, in natural soils and water systems from industrial sources poses a serious threat. Work on defining key parts of Environmental Impact Assessments (EIAs) started with Sadler's 1996 report [3]. He described effectiveness as how well an assessment achieves its intended objectives. Three main types of effectiveness were identified: procedural, material, and financial. Procedural focuses on process structure and policy continuity. The material examines the impact on decision-making and reducing negative environmental impacts. Financial concerns costs and time of EIA (3). Jarvis and Younger (4) studied the EIA of mine water, with pollution from mines being a major water problem in the UK (United Kingdom) and internationally. Kuma et al. (5) researched EIAs in Ghana, proposing an approach for pre-mining groundwater economic and technical impact identification, though neglecting other environmental impacts. Folchi (6) proposed a widely used model to investigate the environmental impacts of open-pit mines, considering only 8 impact factors. The Folchi model has been used by many scholars ever since, but it has a narrow scope and does not account for all impacts (7-9). In 2006, Kitula (10) examined the socioeconomic impacts of mining activities in the Geita district in Ghana. The findings showed that approximately 66% of mining community households' income was derived from the mining industry. Additionally, it was found that less than 5% of Ghana's Gross Domestic Product (GDP) originated from mineral extraction. The small amount added to GDP compared to mining's large local importance means Ghana's mining industry needs more investment. Pandey et al. (11) studied the environmental impacts of the Malanjkhand copper mine in India. They investigated various factors such as acid mine drainage (AMD), impacts on flora and fauna, general environmental pollution, water quality, and impacts on aquatic organisms. Rashed (12) assessed and monitored pollution from the tailings of the Allaqi Wadi Aswan gold mine in southeast Egypt. Aryafar et al. (13) employed a modified Folchi method to assess the environmental implications of the East-Alborz coal-washing plant in northeastern Iran. The researchers used an adapted Folchi approach to analyze the environmental impacts of a coal facility in Iran. Similarly, Northey et al. (14) assessed impacts of copper mining through sustainability report data. By using corporate sustainability reports, they could evaluate the environmental consequences of copper mining operations. Minaei Mobtaker and Osanloo (15) conducted a study examining the potential positive outcomes of mining operations. The research showed mining can provide various economic, social, and environmental benefits based on the evaluation of impacts. Northey et al. (16) evaluated the environmental impacts of copper mining using data from sustainable development reports. They focused on factors like greenhouse gas emissions, fossil fuel consumption, and water consumption. Taušová et al. [17] investigated the socioeconomic impacts of mining over time in Slovakia. Research has found around 4,000 employees work in the Prievidza region directly involved in mining. Additionally, approximately 6,000 more jobs are indirectly supported by or connected to mining activities in the area (17). Amirshenava and Osanloo (18) developed a framework to assess the impact of mining activities on sustainable development indicators. Their model included 14 criteria: 8 environmental criteria, 3 social criteria, and 3 economic criteria. Yankson and Gough (19) studied the influence of gold mining on livelihoods and transformations in the mining scale. The research found that between 2001 and 2011, gold mining contributions to household income increased up to five-fold in certain localities. This suggests mining, particularly artisanal and small-scale gold extraction, played a dramatically heightened economic role for communities over that decade-long period according to the income data analyzed. Von der Goltz and Barnwal (20) conducted an extensive analysis of 800 mines across 44 developing nations, finding mining operations provide considerable long-term economic gains but these are also spatially constrained. They discovered that asset levels were higher for those within 20 km of mines, showing mining wealth mainly stays within close local communities. But for people living farther than 20 km, there was no correlation between mining activity and increased household assets or prosperity. So, while mining boosts local economies, these economic impacts do not spread much past the tight sphere of direct influence around 20 km from mine sites, with the gains mostly confined to nearby local communities close to the mining operations. Argimbaev et al. (21) examined iron-bearing tailings from waste dumps at ore processing facilities in the Kursk Magnetic Anomaly region of Russia. Microscope examination from 90-600x magnification revealed varied particle sizes and shapes indicating potential construction uses for tailings after further processing. Tabasi and Kakha (22) evaluate the environmental impacts of granite quarrying activities near Boog, Iran. By quantifying the impacts of factors on designated environmental components with a systematic fuzzy approach, this research assisted in environmental impact assessments for mining projects. Atienza et al. (23) examined the impacts of mining on urban growth in Chile. Through standard econometric analysis, they discovered that real estate investment expansion primarily correlated with mining activity, copper exports, national monetary fluidity, and regional wages. Consequently, mining income in urban areas appears predominantly influenced by household earnings from mining and the subsequent redistribution of this income into property and asset investments. Hosseinpour et al. (24) proposed a framework of 29 positive and negative impacts; but it is not specific to D&LS mines. Cacciuttolo and Cano (25) analyzed the environmental impacts of gold and copper extraction in Chile and Peru, which considered metallurgical processing. Kumar et al. (26) analyzed the geotechnical properties and remediation of contaminated soil from gold mines in Karnataka, India. The research sought to characterize the contaminated mine soil geotechnically and identify a soil-washing method to prevent surrounding environmental pollution. Sanjuan-Delmás et al. (27) evaluated the life cycle environmental impacts of European copper production using SimaPro and GaBi software. Gümüşsoy et al. (28) investigated the economic potential and environmental consequences of extracting metals from copper flotation slag. Song et al. (29) assessed the environmental conditions in mineral-rich areas of China using remote sensing techniques. The impacts of noise and noise control strategies at the large-scale Zijin copper mine in Serbia was evaluated by Pantelic et al. (30). Dust levels in a Chinese coal mine was estimated by Luan et al. (31) applying machine learning models. Jafarzadeh et al. (32) used numerical modelling to analyze different cover system designs for mine tailing dams in arid regions. The research found that a capillary barrier cover system was most effective at maintaining around 80% saturation in the storage layer, immediately cutting off oxygen diffusion compared to other designs. By optimizing the cover system and controlling oxygen entry parameters, mine waste sites can better reduce AMD. Alsaleh et al. (33) analyzed the effect of geothermal energy output on carbon dioxide emissions across European nations from 1990 to 2021. Heydari et al. (34) proposed a 37-factor social impact assessment model for mining. However, it focuses only on social impacts, not environmental and economic impacts. Heydari and Osanloo (35) proposed a 44-factor environmental impact assessment model for D&LS open-pit mines. In another study, they developed a 28-factor economic impact assessment model (36). The existing studies on the environmental impacts of mining have limitations. None of the research looks at the effects of D&LS open-pit mines comprehensively. The models also do not address all three indexes of sustainable development - environmental, economic, and social - in their assessment. A sustainability model is needed that considers all three dimensions to identify sustainability issues. This type of mine requires a customized sustainability assessment model. The current studies do not fully examine the impacts of D&LS open-pit mines or provide a solution for assessing sustainability in this context by looking at all SD indexes together.

This study aims to (1) combine three separate models for environmental, economic, and social assessment to make a single inclusive sustainability model under different scenarios, (2) calculate a sustainability score for D&LS copper mines from different stakeholders' point of view, and (3) give mine managers and stakeholders a unified tool to inform decisions for more sustainable mining. The model will be verified using the Sungun Copper Mine in Iran.

2. METHODOLOGY

Previous studies proposed individual models for assessing the social, environmental, and economic aspects of copper mine sustainability (34-36). This study combines those three models into one comprehensive sustainability model for D&LS open-pit copper mines. It includes all three sustainable development areas. This helps work towards the Sustainable Development Goals (SDGs). The proposed model involves defining the model scope, collecting data, and getting final results from the three component models, which were developed by the authors. Then it calculates importance weights, scores, and the overall sustainability score. This provides a unified assessment approach. to calculate the sustainability score for each sustainable development (SD) index. Scenarios are then defined to capture various stakeholders' points of view. Finally, the sustainability score for D&LS copper open-pit mines can be determined (see Figure 1).

2. 1. The Scope When modeling the sustainability score of a D&LS open-pit copper mine, the following items should be considered as part of the model scope:

1. Environmental sustainability: This aspect of the model scope should consider the impact of mining activities on the environment, including air and water quality, land use, and biodiversity.
2. Economic sustainability: This aspect should consider the mine's ability to generate economic benefits, such as employment opportunities and contributions to local and national economies. The model should also evaluate the costs associated with D&LS open-pit mining, such as waste disposal and remediation.
3. Social sustainability: This aspect of the model scope should consider the mine's impact on the health, safety, and well-being of workers and local communities, as well as its contribution to the development of local infrastructure and social programs. The model should evaluate the mine's performance in terms of labor standards, community engagement, and social responsibility.

By considering these items in the model scope, a comprehensive assessment of the sustainability performance of a D&LS open-pit copper mine can be obtained.

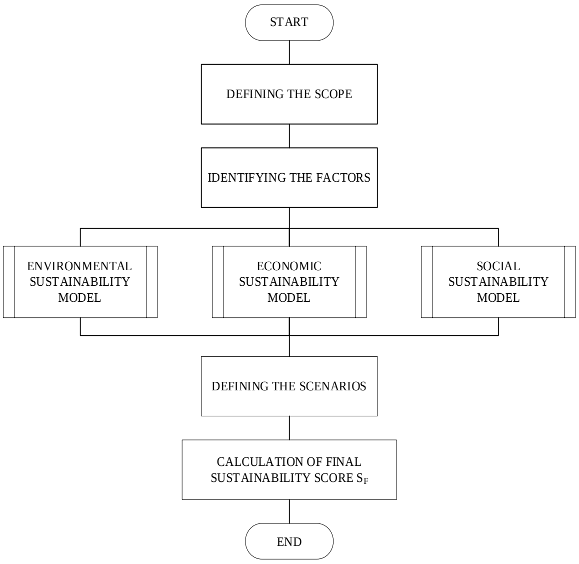

Figure 1. Schematic overview of the proposed model

2. 2. Factors Identification Identifying factors for a sustainability model of a D&LS open-pit copper mine requires a multidisciplinary approach and the collection of data from various sources. The following are some steps that can be taken to identify the factors for the model:

1. Identify the requirements: Based on the items considered in the model scope, identify the requirements for each of the models that need to be considered. The requirements include possible environmental, economic, and social factors.
2. Create a list: Create a list by conducting site visits, surveys, and interviews with stakeholders such as mine workers, local communities, and various sources such as company reports, academic papers, government reports, and industry databases.
3. Ensure completeness of the list: It is important to ensure the list collected is complete by using reliable sources and validated methods.

TABLE 1. Environmental Factors for a Comprehensive Model

No.	Affecting factor	Definition
1	Overburden	Volume of overburden rock removed to access orebody at depths near 1000m
2	Waste rock	Volume of waste rock from low-grade orebodies at depths near 1000m
3	Tailing	Volume of tailings from processing low-grade orebodies mined at depths near 1000m
4	Waste Management	Reusing mine tailings and managing waste materials
5	Acid Mine Drainage	Acid mine drainage potential from pyrite in orebody
6	Ecosystem	Impacts on local biodiversity from habitat loss or fragmentation affecting species
7	Deforestation	Removing forest canopy to access orebody underneath
8	Life Below Water	Impacts on aquatic life from polluting nearby water
9	Ecotoxicity	Toxic impacts and contaminants harming terrestrial and aquatic organisms
10	Ecosystems amend due to reclamation	Improving ecosystem health through habitat, water, and biodiversity restoration

11	Topsoil quality	Topsoil removal eliminates organic matter, nutrients, and microbes. Heavy equipment compacts soil reducing porosity and aeration. Waste rock piles degrade soils.
12	Deep soil quality	Soil properties at depth differ from topsoil due to compaction, depletion, and changes from mining.
13	Terrestrial ecotoxicity	Potential soil contamination varies by project scale and waste volumes.
14	Eutrophication	Mining could affect nutrient-rich surface water through mineral and nutrient inputs.
15	Freshwater ecotoxicity	Freshwater ecotoxicity metrics like heavy metals, pH, and sensitive organisms.
16	Surface water quality	Mining introduces pollutants into waterways affecting surface water quality.
17	Underground water quality	Groundwater contamination potential from leaching chemicals and metals from waste/tailings with long-term impacts.
18	Water Table change	Upward water pressure in open pits presents slope stability and safety issues and impedes mining due to poor drainage.
19	Water consumption	Water demand/consumption depends on project technical aspects and site conditions.
20	Water management	Appropriate water management depends on project/site characteristics.
21	Photochemical ozone formation	Ground-level ozone degrades local air quality and risks respiratory health in communities near mining due to emissions from equipment and machinery.
22	Ozone depletion	Stratospheric ozone depletion from mining operations may occur through emissions of chlorofluorocarbons from equipment, machinery, and explosives used.
23	Atmosphere heat	Alterations to local atmospheric heating and terrestrial radiation levels in open-pit mines can vary depending on pit depth, regional geology, and climate.
24	Temperature inversion	Temperature inversions risk trapped air pollution between mine surface and bottom temperatures.
25	Particulate matter	Particulate emissions from diverse sources like drilling, blasting, crushing, and transport operations.
26	Dust	Dust is pervasive due to heavy equipment, blasting, and in-pit crushing common in D&LS mining.
NO	Affecting factor	Definition
27	Air quality	Air quality impacts from mining dust, diesel exhaust, and blasting emissions.
28	Energy demand/consumption	D&LS open-pits require significant energy prompting efficiency improvements and renewable integration to reduce footprints.
29	Clean/Renewable energy generation	Incorporating renewables like solar, wind, geothermal, and hydro aims to lower emissions and fossil fuel dependence in energy-intensive mining.
30	Fossil fuel depletion/ consumption	Heavy trucks rely mostly on fossil fuels to support open-pit operations.
31	Greenhouse Gas Emissions (GHG)	Mechanization and changes to land use, deforestation, and erosion alter carbon cycles and local climates.
32	Carbon Sinks	Destroying carbon sinks exacerbates carbon dioxide increases contributing to climate change.
33	Surface ground's stability/subsidence	Extensive pre-mining disturbance is required, involving vegetation clearing, topsoil and overburden stripping, excavation works, road and infrastructure development, and waste deposition.
34	Slope Stability	At the regional scale, D&LS open-pit mining usually demands sizeable tracts of land undergo alterations through surface clearing and terrestrial excerption practices
35	Land disturbance	Extensive pre-mining disturbance through clearing, soil/overburden removal, excavation, infrastructure development, and waste deposition.
36	Land use	D&LS open-pits usually demand sizeable, altered tracts of land.
37	Reclamation	Extensive clearing, overburden removal, mining, and infrastructure impact landscapes needing reclamation.
38	Landscape & topography	Operations significantly alter topography through excavations and waste piles visible from afar.
39	Fly rock	Fly rock incidents stem from overcharging, poor fragmentation, blasting issues, and timing.
40	Ground Vibration	Ground vibrations impact stability and safety from blasting, machinery, and seismicity.
41	Transport and access roads	Road development benefits and impacts must be weighed at 1000m depths.
42	Geothermal effect	Deeper exposures result in greater subsurface temperatures from natural gradients.
43	Noise	Drilling, blasting, machinery, and crushing generate noise health concerns.
44	Air overpressure	Explosive shockwaves require control and management.

TABLE 2. Economic Factors for a Comprehensive Model

No.	Affecting factor	Definition
1	Production capacity	Mine scale and production capacity are directly tied.
2	Net present value	As capacity rises with scale, mining income will rise.
3	Net profit	As capacity rises with scale, mining profits will rise.
4	Income	As capacity rises with scale, mining income will rise.
5	Mining & plant equipment	IPCC systems need greater capital than trucks and out-of-pit crushers for D&LS open-pit mines.
6	Infrastructures development	D&LS open-pits require considerable capital for automation, mechanization, robotic equipment, and related infrastructure.
7	Construction	D&LS open-pit mines require considerable capital for construction.
8	Recapitalize	D&LS open-pit mines require considerable capital for depreciation costs.
9	Rate of Return	The larger the investment, the longer to return on investment.
10	Drilling and blasting costs	Drilling and blasting costs are directly tied to production capacity, which reflects the mining scale.
11	Loading costs	Loading costs are directly tied to production capacity, which reflects the mining scale.
12	Haulage costs	Haulage costs are significantly dependent on open-pit depth.
13	Primary Crushing costs.	Primary crushing costs are significantly dependent on open-pit depth.
14	Reclamation costs	Rehabilitation costs are directly related to mine depth and scale.
15	Income tax	Large-scale mines pay greater taxes as production capacity is closely associated with income tax.
16	Royalty	Royalty levels are established by legal frameworks and agreements between mines and authorities.
17	Fixed and indirect costs	Fixed and indirect costs are not affected by depth or scale but do affect regional development.
18	Processing, Smelting, refining	Depth or scale does not directly influence processing costs but affects regional development.
19	Gross domestic product	Higher production from a larger scale means a greater contribution to the country's GDP.
NO	Affecting factor	Definition
20	Export	Increased production from a greater scale also increases contribution to national exports.
21	Business opportunities in other sectors	D&LS open-pits require advanced technology and infrastructure leading to other business opportunities.
22	Foreign exchange	Exchange rates, inflation, and metal prices are outside miner's control, so depth has no direct impact.
23	Inflation	
24	Metal/mineral price	
25	Employment rate & duration	Employment rates and durations in D&LS mines lead to varied economic impacts.
26	Poverty generation or reduction	Income generation will affect poverty reduction/generation.
27	Crime generation or prohibition	Economic crimes may increase or decrease.
28	Regional development	Socioeconomic development occurs due to mining activities in a region.

TABLE 3. Social Factors for a Comprehensive Model

No.	Affecting factor	Definition
1	Job Satisfaction	Job security and salaries are affected by increased depth and scale.
2	Social Relationship	Mining projects affect family life and community communication.
3	Freedom & Justice	D&LS mines influence freedom and justice in nearby communities.
4	Livability	D&LS mines affect food security, living costs, and communication services.

5	Social Infra & Amenity	D&LS mines develop education, health centers, public services, and leisure activities.
6	Political Stability	Political stability affects investment with a direct relation to social impacts.
7	People's Safety	Communication tools and training for safety assurance are vital in D&LS mines.
8	Equipment Safety	Some equipment used in D&LS open-pit mines are partly different in size, type, and usage and their safety assessment is vital.
9	Material Safety	Materials used in D&LS open-pit mines can be different and their safety assessment is important.
10	Employment	D&LS open-pit mines affect employment/unemployment rates (direct, indirect, local, and national employment).
11	Business Opportunity	D&LS open-pit mines create business opportunities above and underhand.
12	Stakeholders Inclusion	Vital to include stakeholders, especially for D&LS open-pit mine lifetimes.
13	Future Generation Rights	It is important to emphasize the efficient depletion of resources for future generations' rights.
14	Land Ownership & Regin Importance	Land ownership is affected by D&LS open-pit mines, which impacts the region's value.
15	Education	D&LS mines can boost local training and education through new technologies.
16	Equipment & Materials Availability	New technologies and unknown environmental conditions in deep open-pit mines will impact the employment of skilled labor.
17	Human Capital	The availability of skilled, trained, and educated human resources is essential in D&LS open-pit mines.
18	Child/Forced Labor	The inclusion of child labor or forced labor in the mining project has a negative social impact.
19	Health and Safety	Community exposure to physical and mental health issues, fatalities, work-related accidents (failure of structures such as dams), and diseases caused by environmental impacts of the mine.
20	Crimes	Crime in the local community (corruption, bribery, robbery, alcoholism, drugs, domestic, and sexual violence).
21	Demographic Changes	Demographic changes due to mining such as the migration of indigenous people to other regions or the migration of professionals to the mining region.
22	Income Generation & Poverty	Income generation in D&LS open-pit mines can impact poverty (poverty prohibition or generation).
23	Wealth Distribution	The distribution of wealth in mining regions should be fair, to include all stakeholders.
24	Tourism Attraction	Mining projects, specifically D&LS projects, can be a positive tourism attraction if managed in line with SDGs, or reduce tourism attraction if not.
25	Culture	Growing tangible culture (buildings, monuments, landscapes, books, works of art, and artifacts) and intangible culture (folklore, traditions, language, and knowledge) due to the mining project.
26	Legislative Frameworks	The mining project needs to apply the legislative frameworks in the regions.
27	Mining Image	Conflict between indigenous people and mining.

The outcome of this step reveals 44 environmental factors, 28 economic factors, and 27 social factors identified for developing a comprehensive sustainability assessment model, respectively (Tables 1 to 3).

2. 3. SD Indexes Models Distinct models for three sustainable development (SD) indices were proposed (34-36). The Fuzzy Delphi Analytic Hierarchy Process (FDAHP) technique was used to calculate the importance weight of each factor. To reduce uncertainty in expert judgments and increase the reliability of their responses, Z-numbers were also used along with FDAHP (formula summarized in Table 4). First, the importance weight for each factor group was calculated. Then their scores were found through scenario-based analysis. This process was repeated for each sustainable development index separately. It resulted in scores for the three distinct SD indexes.

2. 4. Defining Scenarios Scenarios can test how sensitive the assessment is to different stakeholders' points of view, by varied weightings given to each index. To capture the complexity of sustainable development in D&LS copper mines, 10 scenarios were created. Each gave a unique set of weights to the environmental, social, and economic dimensions.

The purpose was to thoroughly look at different trade-offs and priorities of stakeholders. By varying the weights in each scenario, different stakeholder views could be considered. For example, one scenario might emphasize the environment more to minimize ecological harm. Another could weigh social factors higher to focus on community rights and job opportunities. Another could prioritize economics to look at profit, income, and national growth. The defined scenarios capture these varied priorities (Table 5).

Under Equation 12, the final sustainability score for a specific mining site can be determined by multiplying the sustainability score (as shown in Equation 11 in Table 4) of each index by its corresponding weight.

$$S_F = \sum_{n=1}^{3} W_n S_n = \sum_{n=1}^{3} W_n * \left(\sum_{k=1}^{k} W_k * \frac{\sum_1^j S_{Fj}^*}{j}\right) \qquad (12)$$

$$S_F = \sum_{n=1}^{3} W_n S_n = S_{En} W_{En} + S_{Ec} W_{Ec} + S_{So} W_{So} \qquad (13)$$

where

S_n is the final sustainability score for the nth pillar of SD, calculated by the Z-FDAHP technique,

W_n is the assigned weight of the nth pillar of SD, defined in scenarios,

S_{Fj}* is the affecting factor score the jth factor,

W_k is the importance weight of the Kth category, and

S_{En}, S_{Ec}, and S_{So} are the environmental, economic, and social sustainability scores calculated by the Z-FDAHP technique, respectively.

TABLE 4. Summary of formulas for Z-Fuzzy Delphi AHP (34)

No.	Equation	Variables definition	Explanation
(1)	$\alpha = \frac{\int x\mu_{\tilde{R}}(x)dx}{\int \mu_{\tilde{R}}(x)dx}$	$\mu_{\tilde{R}}(x)$ a triangular membership function	Transforming linguistic Z-numbers to fuzzy triangular numbers
(2)	$A_{ij} = (a_{ij}, \delta_{ij}, \gamma_{ij}) * \sqrt{\alpha}$	$\widetilde{A_{ij}}$ the fuzzy representation of the value assigned by experts	Reducing uncertainty of experts' judgments
(3)	$a_{ij} = Min(\beta_{ijk}), k = 1,2,\dots,n$	a_{ij} The minimum value of the questionnaires	The 1st component of the fuzzy number $\widetilde{A_{ij}}$
(4)	$\delta_{ij} = (\prod_{k=1}^{n} \beta_{ijk})^{\frac{1}{n}}, k = 1,2,\dots,n$	β_{ijk} The relative importance of factor i on factor j from the expert's viewpoint k	The second component of the fuzzy number $\widetilde{A_{ij}}$
(5)	$\gamma_{ij} = Max(\beta_{ijk}), k = 1,2,\dots,n$	γ_{ij} The maximum value of the questionnaires	The third component of the fuzzy number $\widetilde{A_{ij}}$
(6)	$\tilde{A} = [\tilde{a}_{ij}]$ $\widetilde{a_{ij}} \times \widetilde{a_{ij}} \approx 1, \forall i,j = 1,2,\dots,n$	$\tilde{A}$ The fuzzy positive reciprocal matrix between the various factors	The different factors' fuzzy positive reciprocal matrix
(7)	$\tilde{Z}_i = [\tilde{a}_{ij} \otimes \dots \otimes \tilde{a}_{in}]^{\frac{1}{n}}$	$\tilde{Z}_i$ The relative fuzzy weight of the factors	The relative fuzzy weight of the factors
(8)	$\widetilde{W}_i = \tilde{Z}_i \otimes [\tilde{Z}_i \oplus \dots \oplus \tilde{Z}_n]^{-1}$	$\widetilde{W}_i$ Fuzzy weight of the ith factor.	$\widetilde{W_i}$ is a row vector that contains a fuzzy weight for the ith factor
(9)	$W_i = (\prod_{i=1}^{3} w_{ij})^{\frac{1}{3}}$	W_i Weight of factor i.	The defuzzification formula
(10)	$S_k = \frac{\sum_1^j S_{Fj}^*}{j}$	S_k is the final score of the Kth category S_{Fj}* is the affecting factor score the jth factor	Scoring the affecting factors
(11)	$S_n = \sum_{k=1}^{k} W_k S_k$	W_k is the importance weight of the Kth category S_n the sustainability score for each SD index	Sustainability Score (S_n)

TABLE 5. Different scenarios for SD index weights

Scenario No	$W_{Environment}$	$W_{Economic}$	W_{Social}
Base Model (Scenario 1)	0.33	0.33	0.33
Scenario 2	1	0	0
Scenario 3	0.6	0.2	0.2
Scenario 4	0.2	0.4	0.4
Scenario 5	0	1	0
Scenario 6	0.2	0.6	0.2
Scenario 7	0.4	0.2	0.4
Scenario 8	0	0	1
Scenario 9	0.2	0.2	0.6
Scenario 10	0.4	0.4	0.2

The final sustainability score ranges from 0 to 10. This shows how well a mine meets its environmental, economic, and social duties to stakeholders.

A score of 10 means full sustainability - the mine handles all three SD indexes very well.

A score of 0 means unsustainability in all three parts. It shows the mine is not managing the environmental, economic, or social aspects properly.

3. VERIFICATION

The Sungun Copper Mine (SCM) in northwest Iran is the second largest copper mine in the region, with the Sarcheshmeh copper mine in the southeast being the largest. It is globally renowned for its large copper deposits, with a total ore reserve of approximately 1.2 billion tons and an average copper grade of 0.67% (see Figure 2). The mine design specifies that the final pit top will have a maximum width of 1.7 km and a minimum width of 1.2 km. The Ultimate Pit Limit (UPL) is anticipated to be at an altitude of 1,400 meters above sea level, resulting in an ultimate pit depth of approximately 900 meters (36).

To evaluate and benchmark the sustainability performance of SCM, a sustainability assessment model has been applied. Previous studies conducted by the authors have determined "the environmental, economic, and social sustainability scores of SCM to be 3.326, 5.298, and 6.364, respectively. By applying 10 different scenarios defined in Table 5, the sustainability score of the SCM mine can be determined under each scenario, using Equation 12.

4. RESULTS

The model applied the 10 scenarios in Table 5 using Equation 12 to determine SCM's final sustainability score. The highest score was achieved under scenario 8, where social factors received the highest weight of 1. This suggests social indicators strongly influence SCM's sustainability performance. Aspects like community impacts and worker conditions are important considerations for long-term sustainable operations. Focusing only on the economic viability of a mining project may overlook these dimensions.

The lowest score was under scenario 2, relying solely on environmental indicators. This implies SCM is not paying enough attention to the environmental impacts of the mining activity.

The highest and lowest scoring scenarios likely show how sensitive the overall results are to how sustainability dimensions are weighted. Valid perspectives exist beyond any single weighting approach.

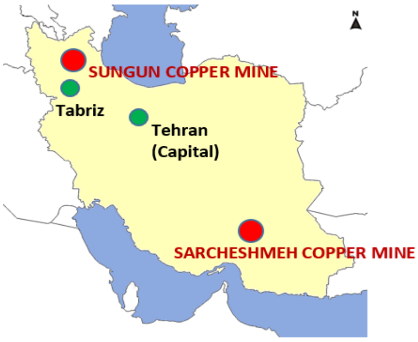

Figure 2. SCM's geographical location (34)

Table 6 shows the score calculations for each scenario. Tables 7 and Figure 3 present the final scores for all ten scenarios.

TABLE 6. Calculations for each scenario (On a scale of 0-10)

Scenario	Calculation	Final Score
Base Model (Scenario 1)	$S_F = \sum_{n=1}^{3} W_n S_n = S_{En} W_{En} + S_{Ec} W_{Ec} + S_{So} W_{So} = 3.326 * 0.33 + 2.111 * 0.33 + 6.364 * 0.33 = 3.894$	3.894
Scenario 2	$S_F = 3.326 * 1 + 2.111 * 0 + 6.364 * 0 = 3.326$	3.326
Scenario 3	$S_F = 3.326 * 0.6 + 2.111 * 0.2 + 6.364 * 0.2 = 3.691$	3.691
Scenario 4	$S_F = 3.326 * 0.2 + 2.111 * 0.4 + 6.364 * 0.4 = 4.055$	4.055
Scenario 5	$S_F = 3.326 * 0 + 2.111 * 1 + 6.364 * 0 = 2.111$	2.111
Scenario 6	$S_F = 3.326 * 0.2 + 2.111 * 0.6 + 6.364 * 0.2 = 3.205$	3.205
Scenario 7	$S_F = 3.326 * 0.4 + 2.111 * 0.2 + 6.364 * 0.4 = 4.298$	4.298
Scenario 8	$S_F = 3.326 * 0 + 2.111 * 0 + 6.364 * 1 = 6.364$	6.364
Scenario 9	$S_F = 3.326 * 0.2 + 2.111 * 0.2 + 6.364 * 0.6 = 4.906$	4.906
Scenario 10	$S_F = 3.326 * 0.4 + 2.111 * 0.4 + 6.364 * 0.2 = 3.448$	3.448

TABLE 7. Final sustainability score for each scenario (On a scale of 0-10)

Sustainability Indexes' scores		**Environment**	**Economic**	**Social**	**Final Sustainability Score**
		3.326	**5.298**	**6.364**	
Sustainability Indexes' Weights	Base Model (Scenario 1)	0.33	0.33	0.33	4.946
	Scenario 2	1	0	0	3.326
	Scenario 3	0.6	0.2	0.2	4.328
	Scenario 4	0.2	0.4	0"4	5.330
	Scenario 5	0	1	0	5.298
	Scenario 6	0.2	0.6	0.2	5.117
	Scenario 7	0.4	0.2	0.4	4.936
	Scenario 8	0	0	1	6.364
	Scenario 9	0.2	0.2	0.6	5.543
	Scenario 10	0.4	0.4	0.2	4.722

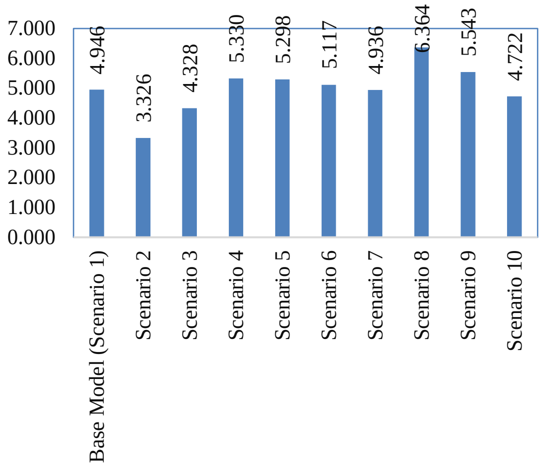

Figure 3. Final sustainability score for each scenario

5. DISCUSSION

The sustainability assessment model was applied to determine the Sungun Copper Mine's (SCM) final sustainability score. SCM is a D&LS open-pit mine in northwest Iran. The results show SCM's sustainability depends on the weights given to environmental, social, and economic factors, from different stakeholders' perspectives.

D&LS open-pit mines can generate long-lasting environmental impacts by stripping away large areas of land and disposing of huge amounts of waste rock and tailings. Surface and groundwater quality may be greatly lowered from acid mine drainage. Greenhouse gas emissions are also high due to energy-intensive mining and materials movement. Irreparable damage to ecosystems and biodiversity may occur without mitigation measures.

At SCM specifically, deforestation of the Arasbaran region could be a concern. Mitigation plans should minimize the project's footprint in forest areas as much as possible to limit habitat loss. Creating new habitats may be needed. Rehabilitation of disturbed forest zones could help accelerate the recovery of this ecosystem since revegetation timelines exceed the mine's lifespan. Priority rehabilitation could help speed up forest recovery.

Economic viability is also important for sustainability. D&LS open-pit mines require massive upfront costs and finances to justify expenses. Financial stability ensures ongoing local jobs and benefits as mining progresses deeper. Neglecting economics risks project cancellation due to a lack of profits, disputes, or funding access.

Prioritizing only social factors also threatens to undermine trust in companies over time. Communities and markets increasingly demand responsibility across all aspects of sustainability.

The mine scored lowest under scenario 2 where only the environment mattered. But exclusively focusing on environmental protection is problematic for major open-pit mines too. It could make projects uneconomical or impose constraints making the core business unviable, without considering economic and social trade-offs. Ignoring economics risks financial instability. Uncontrolled rising costs from unrealistic environmental demands could force early closure. Similarly, dismissing social issues ignores communities near major environmental disruptions. Failing to address social impacts could weaken acceptance over time. This implies that to gain SDG in D&LS open-pit mines, a balanced approach is needed. Rather than favor any single sustainability factor, sustainable development at SCM requires adaptive, integrated strategies that find the right balance between environmental, economic, and social impacts over the long run through close collaboration with stakeholders. This balance can be achieved through scenarios 9, 4, and 6 with scores of 5.543, 5.330, and 5.117 out of 10, respectively.

Deep and Large-scale open-pit mines like SCM present unique difficulties due to their extensive excavation, potential harm to the environment, and social consequences. The proposed model offers an effective way to address these challenges. By including economic, environmental, and social aspects, the final sustainability model in this study understands the complexity of these mining operations and encourages balanced decision-making.

The model examines a wide range of 99 indicators as sustainability measures. This broad examination gives a comprehensive look at how the mine is doing across multiple areas, including issues specific to D&LS open-pit mines.

The Z-FDAHP technique used to calculate importance weights for the sustainability indicators deals with the natural uncertainties and biases involved in assessing sustainability, especially for complex mines. It allows expert input and consensus building, leading to more reliable weights.

The model also analyzes scenarios to assess sustainability performance from different stakeholders' perspectives, under various weightings assigned to each sustainability index. This recognizes sustainability frequently changes as priorities and stakeholder views differ. Looking at different scenarios provides a greater understanding of the relative significance of environmental, social, and economic aspects for sustainable development at these mines. It is important to consider the intended audience of the sustainability report and their particular priorities. The recipient may place more emphasis on some factors over others. Evaluating scenarios allows for a more nuanced analysis that accounts for the end user's perspective. This consideration of the target audience is an important but often overlooked part of environmental impact assessments and sustainability evaluations in previous related studies. Considering who will receive the findings and what matters most to them enhances the relevance and usefulness of the analysis.

The results of this study provide a valuable understanding of prioritizing environmental, social, and economic aspects in D&LS open-pit mines to identify the most sustainable practices under different conditions. This can encourage sustainable practices in mining and help meet sustainable development goals.

6. CONCLUSION

This study developed a comprehensive sustainability assessment model and validated it through application to the Sungun Copper Mine case study. The model takes a holistic, multi-dimensional approach to evaluate mining projects across a wide range of 99 environmental, social, and economic indicators. Its scenario-based structure allows customization based on project contexts and stakeholder perspectives.

Application of the model to Sungun Copper Mine demonstrated its functionality and provided valuable insights into priority issues. Examining varied scenarios highlighted the importance of tailoring assessments based on audience. The results also showed the need for balanced consideration of all sustainability factors. Engaging stakeholders in the application process helps ensure assessments remain grounded in operational realities. Integration of outputs into sustainability strategies and programs supports focused action.

The model incorporates the 99 factors using Z-FDAHP and offers a formula to calculate sustainability scores under scenarios. This tool allows stakeholders to assess adherence to responsible practices. Quantifying performance provides a transparent and measurable representation aligned with sustainability goals. This enhances stakeholder involvement and decision-making.

Considering diverse aspects of sustainable development across multiple scenarios strengthens the model's usefulness across mining contexts. The model fills gaps in knowledge by taking a comprehensive approach tailored to this context.

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Persian Abstract

چکیده

معادن روباز عمیق و بزرگ مقیاس (D&LS) می‌توانند اثرات مختلف محیط‌زیستی، اجتماعی و اقتصادی بر ذینفعان و جوامع محلی، منطقه‌ای، ملی و بین‌المللی داشته باشند. شناسایی این اثرات و داشتن مدل جامعی برای ارزیابی همزمان آنها برای دستیابی به اهداف توسعه پایدار (SD) حیاتی است. در این مطالعه یک مدل ارزیابی پایداری ارائه شده است که شامل ۹۹ عامل تأثیر در بعدهای محیط‌زیستی، اجتماعی و اقتصادی است. امتیاز پایداری با استفاده از تکنیک Z-FDAHP محاسبه شد تا قضاوت شخصی و عدم قطعیت در نظرات متخصصان کاهش یابد. سپس از تکنیک مبتنی بر سناریو برای لحاظ کردن دیدگاه‌های ذی‌نفعان مختلف در مدل استفاده شد. این مدل در معدن مس سونگون در شمال‌غربی ایران پیاده شد. نتایج نشان داد که عملکرد پایداری معدن مس سونگون حساسیت بسیار بالایی نسبت به وزن‌دهی شاخص‌ها دارد. بالاترین امتیاز پایداری با تاکید بر شاخص اجتماعی (امتیاز پایداری ٦/٣٦٤ از ۱۰) بدست آمد که نقش حیاتی تاثیرات پروژه معدنی در جوامع اطراف را روشن می‌سازد. تاکید انحصاری بر شاخص‌های زیست محیطی یا اقتصادی، امتیاز پایداری کمتری داشته و نتایج آن به ترتیب ۳/۳۲٦ و ۵/۲۹۸ بود. رویکرد مبتنی بر در نظرگرفتن همزمان سه شاخص توسعه پایدار با همکاری ذینفعان به معنای اجرای همزمان سه شاخص توسعه پایدار است که توسط امتیازات پایداری ۵/۳۴۵، ۵/۳۳۰ و ۵/۱۱۷ در سناریوهای ۸، ۳ و ۵ به ترتیب نشان داده شده است. مدل ارزیابی پایداری ارائه شده، اطلاعات باارزشی را برای شرکت‌های معدنی و ذی‌نفعان فراهم می‌کند تا بهتر بتوانند تاثیرات پروژه‌های معدنی، بالاخص معادن روباز عمیق و بزرگ مقیاس را بر ابعاد مختلف توسعه پایدار ارزیابی کنند. مدل پایداری ارزیابی ارائه شده به دلیل به کارگیری مجموعه جامع ۹۹ عامل محیط‌زیستی، اجتماعی و اقتصادی؛ توانایی در نظرگرفتن اوزان متفاوت برای شاخص‌ها در سناریوهای مختلف بر اساس دیدگاه ذی‌نفعان؛ و اعتبارسنجی با استفاده از مطالعه موردی، رویکردی جدید و نوآورانه ارائه داده است.