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Abstract

Sustainable development is about creating a balance between development and environment, and it consists of three essential principles: environment, society, and economy. Today, one of the most important challenges in deep open pit mines is the transition from open pit to underground, which has positive and negative impacts on sustainable development indexes. In order to reduce these adverse impacts, the impact of various parts of the transition operation on these indexes should be evaluated and corrective and preventive measures should be implemented. In this study, using a hybrid semi-quantitative approach, the effects of the transition in the Songun copper mine were evaluated. The obtained results showed that the transition in Songun copper mine has the greatest impact on the economic index of sustainable development with a value of 67.72 percent. In addition, the amount of impact of transition in this mine on environmental and social index is 41.74 and 39.84% respectively. In the meantime, the most significant impact was determined on components such as production rate and productivity, mine life, operation and capital cost, mineral value and income per ton of ore, mine closure (and reclamation) cost, Initial investment rate of returns, post–mining land use type.

Keywords

Open-pit to underground mining, Sustainable development, AHP method, TOPSIS method

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Evaluating the impacts of the transition from open-pit to underground mining on sustainable development indexes

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Abstract

Sustainable development is about creating a balance between development and environment, and it consists of three essential principles: environment, society, and economy. Today, one of the most important challenges in deep open pit mines is the transition from open pit to underground, which has positive and negative impacts on sustainable development indexes. In order to reduce these adverse impacts, the impact of various parts of the transition operation on these indexes should be evaluated, and corrective and preventive measures should be implemented. In this study, using a hybrid semi-quantitative approach, for the first time, various factors, and conditions during the transition from open pit to underground mining, and the sustainable indexes (economic, social, and environmental) sub-criteria affected by these factors and conditions were identified. After identifying various factors, conditions, and sustainable indexes sub-criteria, the positive and negative effects of various factors of the transition from open pit to underground mining on sustainable development indexes were evaluated. The obtained results showed that the transition in the Songun copper mine has the greatest impact on the economic index of sustainable development, with a value of 67.72 percent. In addition, the amount of impact of transition in this mine on the environmental and social index is 41.74 and 39.84 percent, respectively. In the meantime, the most significant impact was determined on components such as production rate and productivity, mine life, operation and capital cost, mineral value and income per ton of ore, mine closure (and reclamation) cost, Initial investment rate of returns, post-mining land use type.

Keywords: open-pit to underground mining, sustainable development, AHP method, TOPSIS method

1. Introduction

Today, the main problem of deep open-pit mines is to continue mining with the open-pit method or to change the way to one of the underground methods. Changing the open-pit mining method to one of the underground mining methods, which is known as the transition operation from open-pit to underground mining, has significant impacts on sustainable development indexes (economic, social, and environmental). Therefore, it is necessary that these impacts on each of the indexes of sustainable development are carefully examined, and solutions are provided. Achieving sustainable development in transition operations from open-pit to underground mining requires environmental, economic, and social considerations, and therefore achieving this goal is possible by evaluating the environmental, economic, and social impacts. It is with the use of accurate assessment that the identify impacts of the transition from open-pit to underground mining on the environment, economy, and society and take the necessary preventive measures [1].

Not paying attention to the destructive and unwanted impacts of mining is against the principles of sustainable development. The concept of sustainable development was first recognized in 1992 at the International Earth Conference in Brazil. According to the definition presented for this concept at this conference, sustainable development is a development in which the current generation can

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meet their needs without impairing and destroying the ability of future generations to meet their needs. In this regard, mining industries seek to improve their environmental and social performance, based on the principles of sustainable development, at the same time as improving economic performance and increasing profitability [2].

Sustainable development consists of creating a balance between development and the environment and consists of three essential principles of environment, society, and economy. All three of these parameters are related to each other, and the imbalance in each will upset the balance in other parts [3]. The Mining industry is one of the main means of economic growth and social welfare in many countries. “Paying attention to sustainable development in the mining activities can reduce environmental problems and have positive social and economic effects” [4]. In modern mining, the indicators of sustainable development have been given special attention, and the extraction and processing of minerals are in such a way that sustainable development is maintained. This issue has caused industrialized countries to enjoy more prosperity and wealth [5].

Many instrumental studies have been conducted in the field of evaluating the various effects of mining activity with a hybrid semi-quantitative approach and multi-criteria decision-making methods. The most critical weakness of these methods is that they are not comprehensive and do not consider the combined extraction mode. In addition, most of these researches focus on open-pit mines and environmental impacts, and all three sectors of sustainable development, especially social ones, have been less addressed.

Table 1 provides a comparison of the characteristics of the current study with other studies performed to determine the impacts of mining activity (open-pit, underground, and combined).

Firstly, to assess the environmental, economic, and social impacts of the transition from open-pit to underground mining in Songun copper mine, a matrix structure has been used, which incorporates the influential factors and the environmental, economic, and social components of the dimensions of this matrix. They donate to decide and determine the influential factors, the score of the influential factors, and the impact of the influential factors on the environmental, economic, and social components. Also, expert opinions have been used. By quantifying the qualitative comments, the overall impact on environmental, economic, and social component was determined.

In this research, to complete the previous studies, innovations were presented, the most important of which was determining the effects of various factors and conditions in the combined open pit-underground mining mode on sustainable development indexes. According to the authors' reviews, a study with this goal was examined for the first time. The significant factors and different conditions during the transition that had an impact on various economic, social, and environmental sectors were determined through field surveys, detailed research conducted, and using the opinions of experts in this field (all over the world). Also, for the first time, economic, social, and environmental sub-criteria were prepared, which were affected by various factors and conditions during the transition.

In the following first case study (Songun copper mine) is introduced. The methodology of the stages of evaluation of the effects of transition operations on sustainable development indicators was presented. According to the presented stages, the results and findings were expressed and finally discussed and concluded.

2. Methodology

2.1. Case study: Songun copper mine

The potential reserves of this mine are more than 1 billion tons, the mineable reserves (concurring to the discoveries made) are approximately 796 million tons, and the total definite, probable, and possible reserves around the Songun copper mine are approximately 1.7 billion tons of copper ore with a grade of 0.61 percent is. Figure 1 shows the location of the Songun copper mine. The Songun copper mine is one of the biggest open-pit and critical copper mines in Iran, and the Center East, which is found 105 km northeast of Tabriz, 75 km northwest of Ahar, and 28 km north of Varzeqan, borders to Azerbaijan and Armenia countries [7].

To have an initial view of the mine conditions and reveal the general characteristics of the mine, a summary of the technical, economic, social, and environmental information of the Songun copper mine is presented in Table 2.

In the continuation of this section, the method of solving the problem and its steps are explained.

2.2. Steps to evaluate the impacts of transition operations on sustainable development indexes

As mentioned before, the qualitative methods for examining and evaluating different projects are not

Table 1. Comparison of the characteristics of the present study and the most important studies to determine the effects of mining activity (open pit, underground, and combined) on sustainable development indicators [own research].

Researcher(s)	Country (case study)	Year	Comprehensive[a]	OP	UG	OPUG	EC	SO	EN	Research focus	Commodity
Current study	Iran	2022	✓	✓	✓	✓	✓	✓	✓	Determining the impacts of transition operation on sustainable development indexes	Metals
Rakhmangul et al. [6]	Russia	2022		✓			✓	✓	✓	Selection of Open-Pit Mining and Technical System's Sustainable Development Strategies Based on MCDM.	Copper
Badakhshan et al. [7]	Iran	2021		✓			✓	✓	✓	Evaluation Impact of Mining Activities on Sustainable Development indexes	Copper
Zhu et al. [8]	China	2020		✓					✓	Observing the impacts of open-pit mining on the eco-environment employing a moving window-based inaccessible detecting environmental index	Several metal mines
Amirshenava and Osanloo [9]	Iran	2019		✓			✓	✓	✓	A hybrid semi-quantitative approach for impact assessment of mining activities on sustainable development indexes	Copper
Amirshenava and Osanloo [10]	Iran	2018		✓			✓	✓	✓	Mine closure risk management: An integration of 3D risk model and MCDM techniques	Copper
Shahba et al. [11]	Iran	2017		✓					✓	Application of multi-attribute decision-making strategies in SWOT investigation of mine squander administration (case consider: Sirjan's Golgohar press mine, Iran)	Iron
Couto Garcia et al. [12]	European North and Northwest Russia	2106		✓	✓			✓		Social sustainability in northern mining communities	Metals
Yavuz and Lacin Altay [13]	Turkey	2015		✓					✓	Reclamation project selection using fuzzy decision-making methods	Magnesite
Govindan et al. [14]	India	2014			✓			✓		Assessing the drivers of corporate social duty within the mining industry with the multi-criteria approach: A multi-stakeholder viewpoint	Coal
Józef Dubiński [15]	Polish	2013		✓	✓		✓	✓	✓	Portrayal of mineral assets and the request for them, taking under consideration the dynamics and worldwide patterns within the economy of crude materials	Coal

[a] Comprehensive: includes the status of all three indexes of sustainable development (Economic, Social, and Environmental). OP: open-pit mining, UG: underground mining, OPUG: combined open-pit − underground mining, EC: economic, SO: social, EN: environmental.

Fig. 1. Location of Songun copper mine [7].

very accurate, and that is why there is a need to make an effort to create and apply mathematical techniques in evaluating various projects. Based on this, a semi-quantitative-qualitative method has been used to assess the impact of the transition from open-pit mining to underground mining on sustainable development indexes based on quantitative and mathematical methods.

This research, using field surveys and the opinions of mining experts (especially those who are involved in transition issues from open-pit to underground mining and have sufficient technical knowledge and experience in this field), seeks to evaluate the impacts of the transition from open-pit to underground mining on sustainable development indexes (economy, society and, environment). The present research examines mines with the potential of combined open-pit-underground mining.

Deciding whether to continue mining with an open pit method or to change to one of the underground methods is one of the most critical challenges of deep open pit mines reaching their absolute limits. With the deepening of the peat, the stripping ratio increases to such an extent that the continuation of mining with the underground method is more economical than the open method.

To make an accurate assessment, the opinions of 31 experts with sufficient technical knowledge and field experience were used in this research. Out of these 31 experts, 18 specialize in extraction, four people in the environment, three people in processing, two in exploration, three people in economics, and two people in sociology.

In this research, first by studying the research conducted in the field of transition from open-pit to underground mining and field survey of several mines with the potential of combined extraction in Iran, 20 main factors (caused by the activities of transition from open-pit to underground mining) affecting sustainable development indexes selected.

Table 2. Technical, economic, social, and environmental information of Songun copper mine [16].

Options	Parameters	Symbols	Current value or characteristic	Predicted value or characteristic
Economic and technical	Geological resources	$GR_{OP\&UG}$	5 billion tons	More than 5 billion tons
	OP Mining reserves	MR_{OP}	596 million tons	It is expected that the extraction from this part of the mine will increase.
	UG Mining reserves	MR_{UG}	–	200 million tons
	Underground mining method	UMM	–	Block caving
	Crown pillar	CP	It does not exist (in caving mining, the crown pillar is meaningless)	It does not exist
	Mining equipment	ME	–	LHD Diesel 7 and 10 yd3, Jumbo and picking hammers, jaw crushers 47″ 63” (up to 2 m fragment sizes)
	Metal price	MP	9.263 US$	According to the world conditions, there is a very high probability of an increase.
	Average grade	AG	0/61	According to the discoveries in the supergene sector, there is a possibility of increasing the average grade.
	OP cut-off grade	OP_{CG}	1.5 g/t	–
	UG cut-off grade	UG_{CG}	–	2.45 g/t
	Economic discount rate	DC	12%	–
	Processing cost	PC	9.2 (US$/t)	–
	OP mining cost	OP_{MC}	2.5 (US$/t)	–
	UG mining cost	UG_{MC}		2.7 (US$/t)
	OP mining rate	OP_{MR}	41 095 (t/d)	The possibility of increase
	UG mining rate	UG_{mr}	–	24 657 (t/d)
	OP mining recovery	OP_R	98%	–
	UG mining recovery	UG_R	–	100%
Environmental and social (factors affecting the social conditions and environmental costs of mines)	Human Development Index (HDI)	F_{HD}	The United Nations, to measure human development in a country, developed the Human Development Index. HDI is quantified by looking at a country's human development, such as education, health, and life expectancy. HDI is set on a scale from 0 to 1, and most developed countries have a score above 80. HDI can be used to determine the best countries to live in, as more developed countries typically offer their residents a higher quality of life [16].	Proposed mine fall in high conservation value areas
	Mining scale	F_{MS}	The scale of the mine in this study is determined based on the annual production of the mine.	Large-scale mining” (LSM)
	Location of the mine relative to the settlement	F_{LM}	The location of the mine in relation to urban or rural residential areas is determined based on their distance (kilometers).	According to the latest statistics Nations Human Development Data Center
	Mining method	F_{MM}	The mining methods are based on Hartman, proposed methods for surface and underground metal mines.	Open pit and block caving
	Type of mineral	F_{TM}	Depending on the type of mineral, the impact will vary.	Copper
	Environmental and ecosystem sensitivities of the mining area	F_{EES}	Environmental and ecosystem sensitivities include proximity of the mine to the river, location in the groundwater path, proximity to specific plant species in the area, endangered animal species, and so on.	Proposed project fall in high conservation value areas
	Employment of natives	EN	57% of Songun copper mine personnel are local people.	This ratio is increasing
	Development of infrastructure in the suburbs of the mine	DIS	15% of the government rights of Songun mine will be used for the development of Varzeghan city.	The possibility of increase

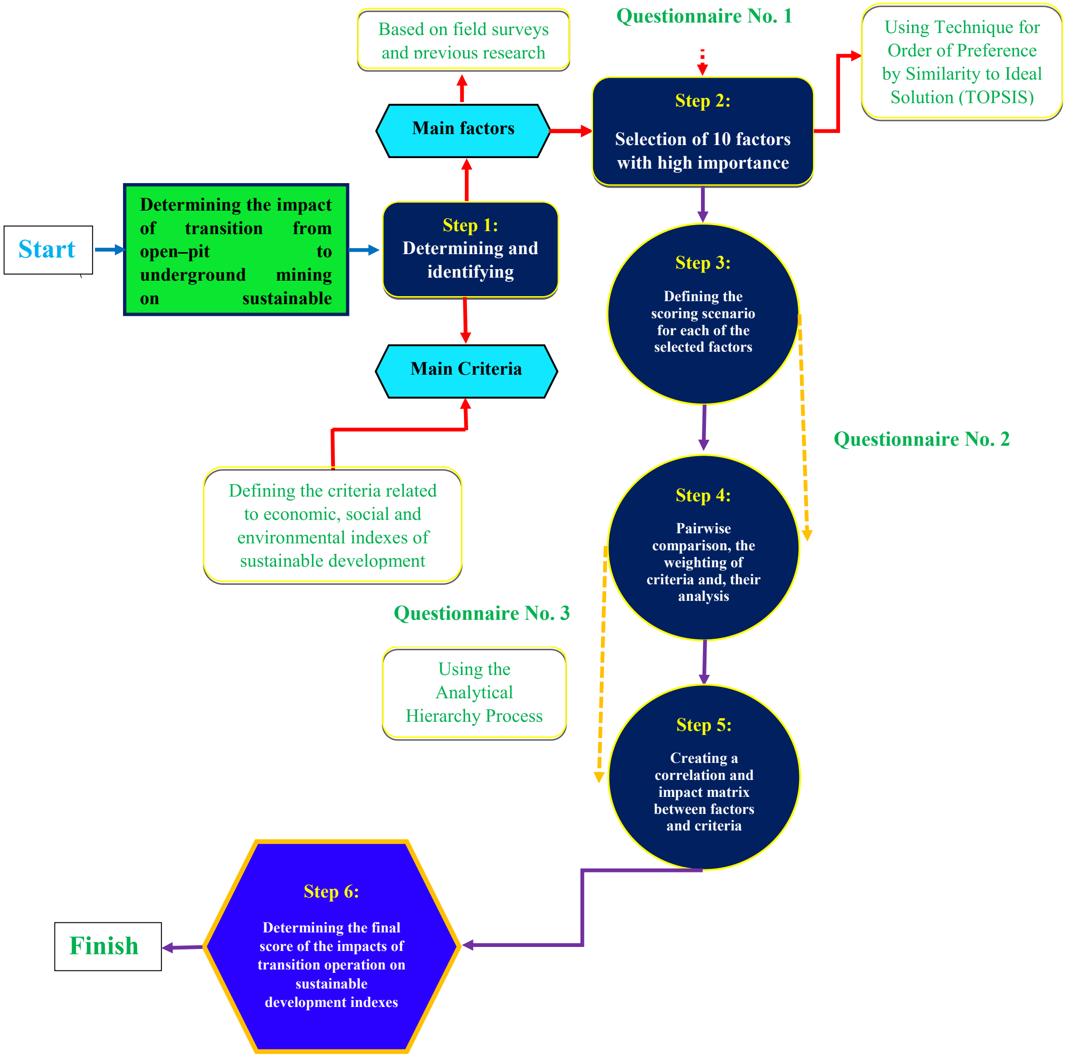

Fig. 2. The stages of evaluating the impact of the transition from open pit mining to underground mining on sustainable development indexes.

In addition, 30 criteria related to economic, social, and environmental sectors (10 items each) were determined and identified. On the basis of the scoring of each of the 20 primary factors based on the experts' opinions and using the TOPSIS method, 10 essential and high-impact main factors were selected (Questionnaire No. 1 sent to experts). In addition, scoring scenarios were defined for each of the 10 factors (Questionnaire No. 2 sent to experts). Next, pairwise comparison, the weighting of the criteria, and then their analyses using the AHP method was made (Questionnaire No. 3 sent to experts). The correlation matrix and the impact between the factors and criteria were established, and the range of changes was determined for each element. Finally, the final score of the effects of the transition from open-pit to underground mining on sustainable development indexes was determined. The stages of evaluating the effect of the transition from open-pit mining to underground mining on sustainable development indexes are according to Fig. 2.

3. Results and discussion

3.1. Determining and identifying the primary factors and criteria

According to the studies carried out on the researches related to the problem of transition from open pit mining, using the knowledge and experiences of the personnel of mines with the possibility of combined extraction and field visits and surveys of some mines with the potential of combined extraction, such as Angoran lead and zinc mine, Sarcheshmeh and, Songun copper mines, 20 of the

Table 3. Factors considered in this research.

Parameters	symbol
Transition depth	F_1
Concurrency or asynchrony of transition operations	F_2
Existence or absence of crown pillar between open and underground mine	F_3
Depth of ore body expansion	F_4
Ore body slope	F_5
Ore body dimensions (volume)	F_6
Ore body shape	F_7
Transition time	F_8
Geomechanical aspects of the ore body	F_9
Geotechnical characteristics of the hanging wall and footwall	F_{10}
Type of mining method in combined mode	F_{11}
Type of use of mine wastes (and tailings)	F_{12}
Areas affected by mining activity (footprint)	F_{13}
Government laws and related restrictions	F_{14}
Existence of technical and operational knowledge of the mining method	F_{15}
Geological uncertainty (grade and tonnage)	F_{16}
Economic uncertainty (metal price changes)	F_{17}
Political uncertainty (change of governments)	F_{18}
Significant progress in loading and haulage equipment (in terms of engine power and capacity)	F_{19}
Ultimate reserves depth	F_{20}

main factors resulting from the transition from open-pit mining to underground mining, which had positive and negative impacts on sustainable development indicators, were determined (Table 3). “In addition, 30 criteria related to economic, social, and environmental sectors (10 items in each sector), which are affected by the main factors, were determined and identified according to Table 4.”

3.2. Selection of 10 factors with high importance using the TOPSIS method

The scoring method for each of the 20 primary factors to select 10 critical factors in the transition operation from open pit to underground mining and continue working with those 10 factors (Questionnaire No. 1 sent to experts) was based on Table 5.

The average scores of experts to questionnaire 1 to determine the 10 most important, influential factors are according to Table 6.

To rank the factors and determine 10 crucial factors based on experts' opinions, the TOPSIS method was used. The results of this ranking are shown in Table 7. The continuation of work and evaluations were done based on 10 factors related to ranks 1 to 10.

3.3. Defining the scoring scenario for each of the selected factors (Case study: Songun copper mine)

Table 4. Criteria considered in this research.

Criteria	Sub-criteria	symbol
Economic	Costs of health, safety, and environmental protection	C_1
	Production rate and productivity	C_2
	The hidden value of technology advances and insights	C_3
	Mine life	C_4
	Operation and capital cost	C_5
	Mineable ore tonnage	C_6
	Mineral value and income per ton of ore	C_7
	Mine closure (and reclamation) cost	C_8
	Dilution rate and ore loss rate	C_9
	Initial investment rate of returns	C_{10}
Environmental	Green mining (principle protection of resources and energy)	C_{11}
	Post-mining land use type	C_{12}
	Management of waste pollutants	C_{13}
	Use green space to help protect the environment	C_{14}
	HSEC management system	C_{15}
	Reduce pollution and environmental degradation	C_{16}
	Bed coordination (area ecosystem)	C_{17}
	Ground surface subsidence	C_{18}
	The principle of respect for the mining site	C_{19}
	Mine effluent management	C_{20}
Social	Increasing the employment rate of indigenous people	C_{21}
	Improve employee performance	C_{22}
	Skills training	C_{23}
	Health (safety and usefulness) for people inside the mine	C_{24}
	Infrastructure development	C_{25}
	Life expectancy	C_{26}
	Communication with local communities	C_{27}
	Other local community issues	C_{28}
	Revival of cultural and regional identity	C_{29}
	Considering the interests of the next generation and the present together	C_{30}

Table 5. How to score the factors in order to determine the most important ones [own research].

Importance	Score assigned
Very low	1
Low	2
Medium	3
High	4
Very high	5

The definition of the scoring scenario for each of the 10 primary factors according to different conditions and their impact (Questionnaire No. 2 sent to experts), along with the average scores (according to the values in Table 8), are given in Table 9.

Table 6. Average scores of experts to questionnaire 1 to determine 10 important influential factors [own research].

Parameters	Score assigned
Transition depth	5
Concurrency or asynchrony of transition operations	3.92
Existence or absence of crown pillar between open and underground mine	3.95
Depth of ore body expansion	3.86
Ore body slope	4.08
Ore body dimensions (volume)	3.21
Ore body shape	3.17
Transition time	3.15
Geomechanical aspects of the ore body	3.84
Geotechnical characteristics of the hanging wall and footwall	3.7
Type of mining method in combined mode	4.35
Type of use of mine wastes (and tailings)	2.66
Areas affected by mining activity (footprint)	2.96
Government laws and related restrictions	3.46
Existence of technical and operational knowledge of the mining method	4.17
Geological uncertainty (grade and tonnage)	3.84
Economic uncertainty (metal price changes)	3.95
Political uncertainty (change of governments)	3.14
Significant progress in loading and haulage equipment (in terms of engine power and capacity)	4.34
Ultimate reserves depth	4.05

3.4. Pairwise comparison, the weighting of criteria, and their analysis with AHP

Pairs were compared, and the criteria were weighed and then analyzed using the Analytic hierarchy process method (Questionnaire No. 3 sent to mining experts). This questionnaire shows the importance of each index over the other. Numbers are selected from 1, 3, 5, 7, and 9. In this scoring, the number 9 indicates that the importance of the factor is much greater than the factor with which it is compared, and the number 1 means that both factors are equally important. The average scores given by mining experts are shown in Table 10.

Table 7. Ranking results of influential factors [own research].

Parameters	Symbol	Rank
Transition depth	F_1	1
Type of mining method in combined mode	F_{11}	2
Significant progress in loading and haulage equipment (in terms of engine power and capacity)	F_{19}	3
Existence of technical and operational knowledge of the mining method	F_7	4
Ore body slope	F_5	5
Ultimate reserves depth	F_{20}	6
Economic uncertainty (metal price changes)	F_{17}	7
Existence or absence of crown pillar between open and underground mine	F_{15}	8
Concurrency or asynchrony of transition operations	F_2	9
Geological uncertainty (grade and tonnage)	F_{16}	10

Table 8. How to score the factors based on their impact [own research].

The extent of the impact	Score assigned
Affectless	1
Very low impact	2–3
Low impact	4–5
Medium impact	6–7
High impact	8–9
Very high impact	9–10

After forming a pairwise comparison matrix between the criteria, each row was divided into the sum of the column values. Finally, the relative weight of the criteria was obtained by calculating the sum of the row values (AHP method). Table 11 shows the weight of each of the criteria.

3.5. Creating a correlation and impact matrix between factors and criteria

The impact factors on sustainable development components are given as (VH) very high impact, (H) high impact, medium impact (M), low impact (L), very low impact (VL), and affectless (Z). To score the questionnaires the experts, the number 0 was given for the influential factor, 2 for very low impact, 4 for low impact, 5 for medium impact, 7 for high impact, and 9 for very high impact. In the following, the average points given by the experts to the 10 selected factors according to the scenarios that were defined for each of these impact factors (10×1 matrix) were multiplied in the weighted values matrix of the factors influencing the components of sustainable development (1×10 matrix) and sustainable development evaluation matrix was obtained.

The resulting sustainable development evaluation matrix was normalized. Next, the weights obtained using the AHP method (in the form of a diagonal matrix) were multiplied in the normalized matrix, and the weighted normalized correlation matrix was obtained according to Table 12.

3.6. Score of sustainable development criteria (worst case)

The transcript of the scoring scenario for each of the 10 principal factors is multiplied by the weighted standard correlation matrix, assuming the highest score (10) becomes a 1-in-10 matrix. In this case, the maximum score of each sustainable development criterion (worst case) is obtained according to Table 13.

Table 9. Size values or importance of influential factors for an ideal mine with standard conditions and Songun copper mine [own research].

Factors	Possible options	Score range	Average score	Symbol
Transition depth (*TD*)	$TD > 1000$ m	$10 \leq S \leq 8$	7.04	F_1
	600 m $< TD \leq 1000$ m	$4 \leq S < 8$		
	$TD \leq 600$ m	$1 \leq S < 4$		
Type of mining method in combined mode	A method with high productivity (caving methods)	$10 \leq S \leq 8$	7.74	F_{11}
	A method with medium productivity (sublevel stopping with several workshops)	$4 \leq S < 8$		
	A method with limited productivity (other methods)	$1 \leq S < 4$		
Significant progress in loading and haulage equipment (in terms of engine power and capacity)	Significant progress in the underground mining sector	$10 \leq S \leq 6$	5.22	F_{19}
	The same progress in both open pit and underground mining sections	$4 \leq S < 6$		
	Significant progress in the open pit sector	$1 \leq S < 4$		
Existence of technical and operational knowledge of the mining method	Having enough technical knowledge and experience to implement underground mining methods	$10 \leq S \leq 4$	4.45	F_7
	Lack of technical knowledge and sufficient experience to implement underground mining methods	$1 \leq S < 4$		
Ore body slope (*OBS*)	$OBS \geq 45$	$10 \leq S \leq 8$	6.31	F_5
	$25 \leq OBS < 45$	$4 \leq S < 8$		
	$25 > OBS$	$1 \leq S < 4$		
Ultimate reserves depth (*URD*)	$URD < 1000$ m	$1 \leq S < 4$	8.33	F_{20}
	$1000 \leq URD < 2000$ m	$4 \leq S < 8$		
	$URD \geq 2000$ m	$10 \leq S \leq 8$		
Economic uncertainty (metal price changes)	Irregular and severe changes	$1 \leq S < 3$	7.34	F_{17}
	Irregular and gentle changes	$3 \leq S < 5$		
	Uniform price reduction	$5 \leq S < 8$		
	Uniform price increase	$8 \leq S \leq 10$		
Existence or absence of crown pillar between open and underground mine	Existence crown pillar	$1 \leq S < 5$	7.22	F_{15}
	Absence crown pillar	$5 \leq S \leq 10$		
Concurrency or asynchrony of transition operations	Concurrency	$1 \leq S < 5$	6.95	F_2
	Asynchrony	$5 \leq S \leq 10$		
Geological uncertainty (grade and tonnage)	Estimating grade and tonnage more than their actual amount (optimistic)	$1 \leq S < 5$	8.45	F_{16}
	Estimating grade and tonnage lower than their actual amount (pessimistic)	$5 \leq S \leq 10$		

Table 10. Average scores (geometric average) given by experts (scores from 1 to 9) [own research].

	F_1	F_{11}	F_{19}	F_7	F_5	F_{20}	F_{17}	F_{15}	F_2	F_{16}
F_1	1	5.17109847	8.3463995	7	7.54816493	7.54816493	7.5481649	9	8.13925625	7.548165
F_{11}	0.19338251	1	6.32790032	2.27075225	1.11612317	3.49684095	3.1572293	6.76838784	4.75100108	5
F_{19}	0.11981214	0.1580303	1	1.39038917	1	3.80604184	0.8011296	4.82865149	2.82874633	0.80113
F_7	0.14285714	0.4403827	0.71922309	1	1.11612317	1	1.3903892	1.11388194	1.39038917	0.33
F_5	0.13248253	0.89595846	1	0.89595846	1	0.71705783	3.1572293	2.68787538	1	0.893261
F_{20}	0.13248253	0.2859724	0.26274015	1	1.39458766	1	3	1.11612317	1	0.459752
F_{17}	0.13248253	0.31673341	1.24823746	0.71922309	0.31673341	0.33333333	1	5.17109847	1	1
F_{15}	0.11111111	0.14774567	0.20709716	0.89776121	0.37204106	0.89595846	0.1933825	1	0.29011647	0.641164
F_2	0.12286135	0.21048196	0.35351349	0.71922309	1	1	1	3.44689147	1	0.799521
F_{16}	0.13248253	0.2	3.03030303	1.11949348	1.11949348	2.17508745	1	1.55966349	1.25074903	1

Table 11. The relative weight of criteria using the AHP method [own research].

Factors	The relative weight of criteria	Rank
F_1	0.423	1
F_{11}	0.164	2
F_{19}	0.068	3
F_5	0.066	4
F_7	0.064	5
F_{20}	0.050	6
F_{17}	0.047	7
F_{15}	0.047	8
F_2	0.046	9
F_{16}	0.025	10

Table 12. Weighted normalized correlation matrix [own research].

F_1	F_1	F_1	F_1	F_1	F_1	F_1	F_1	F_1	F_1	F / I	
0	2.258297761	1.357673747	1.384947596	1.65554456	1.605757622	2.630066154	2.499531656	11.41954292	14.89079684	C_1	Economic
1.054390748	2.258297761	1.357673747	1.731184495	2.0694307	2.007197027	2.630066154	3.213683558	11.41954292	26.80343432	C_2	
1.054390748	1.290455863	1.357673747	1.731184495	1.65554456	1.605757622	2.045607009	3.213683558	0	5.956318737	C_3	
1.476147048	2.903525692	1.357673747	2.423658292	3.72497526	3.612954649	1.461147863	2.499531656	6.344190509	26.80343432	C_4	
1.897903347	2.903525692	0	3.11613209	3.72497526	3.612954649	2.630066154	3.213683558	11.41954292	26.80343432	C_5	
1.897903347	2.258297761	0.678836873	3.11613209	2.89720298	2.810075838	2.045607009	1.428303803	6.344190509	20.84711558	C_6	
1.897903347	2.258297761	0	3.11613209	2.0694307	2.007197027	2.045607009	1.428303803	5.075352407	20.84711558	C_7	
0	2.258297761	2.375929057	1.384947596	2.0694307	2.007197027	1.168918291	1.785379754	6.344190509	20.84711558	C_8	
0.843512599	2.258297761	1.697092184	0	1.65554456	0	2.045607009	1.785379754	8.881866713	11.91263747	C_9	
1.476147048	2.258297761	1.357673747	2.423658292	2.0694307	2.007197027	1.461147863	1.785379754	0	20.84711558	C_{10}	
0.421756299	1.613069829	2.375929057	0.692473798	1.65554456	1.605757622	1.168918291	2.499531656	6.344190509	14.89079684	C_{11}	Environmental
0.843512599	2.258297761	2.375929057	1.384947596	2.0694307	2.007197027	1.168918291	1.428303803	6.344190509	26.80343432	C_{12}	
0.843512599	1.613069829	2.375929057	1.384947596	1.65554456	1.605757622	1.168918291	1.785379754	8.881866713	20.84711558	C_{13}	
0.421756299	1.290455863	1.697092184	0.692473798	1.65554456	0	1.168918291	1.785379754	8.881866713	14.89079684	C_{14}	
0.421756299	1.290455863	1.697092184	0.692473798	1.65554456	0	1.168918291	1.428303803	5.075352407	14.89079684	C_{15}	
0.843512599	2.258297761	1.357673747	0	1.65554456	1.605757622	1.461147863	1.428303803	11.41954292	20.84711558	C_{16}	
0.843512599	2.258297761	1.357673747	1.384947596	2.89720298	2.810075838	1.168918291	1.428303803	6.344190509	20.84711558	C_{17}	
0.421756299	2.903525692	2.375929057	0	2.89720298	2.810075838	1.168918291	0.714151902	11.41954292	20.84711558	C_{18}	
0	1.290455863	1.697092184	1.384947596	1.65554456	1.605757622	1.168918291	0	6.344190509	11.91263747	C_{19}	
0.843512599	0	1.357673747	1.384947596	1.65554456	1.605757622	2.045607009	2.499531656	6.344190509	5.956318737	C_{20}	
0.843512599	1.290455863	1.357673747	1.384947596	1.65554456	1.605757622	2.045607009	2.499531656	6.344190509	26.80343432	C_{21}	Social
1.054390748	1.290455863	1.357673747	1.731184495	1.65554456	1.605757622	2.045607009	1.785379754	5.075352407	20.84711558	C_{22}	
0.843512599	0	1.357673747	1.384947596	0	1.605757622	2.630066154	3.213683558	6.344190509	20.84711558	C_{23}	
0.843512599	2.258297761	2.375929057	1.384947596	1.65554456	0	1.461147863	1.428303803	11.41954292	14.89079684	C_{24}	
1.054390748	1.613069829	1.697092184	1.731184495	1.65554456	1.605757622	2.630066154	2.499531656	8.881866713	20.84711558	C_{25}	
0.843512599	1.613069829	1.357673747	0	2.0694307	2.007197027	1.168918291	1.785379754	6.344190509	20.84711558	C_{26}	
0	1.290455863	1.357673747	1.384947596	0.82777228	0	1.168918291	1.428303803	6.344190509	11.91263747	C_{27}	
0.843512599	1.290455863	0	1.384947596	0	1.605757622	0	1.428303803	6.344190509	11.91263747	C_{28}	
0	1.290455863	1.357673747	1.384947596	0	1.605757622	1.461147863	1.428303803	5.075352407	14.89079684	C_{29}	
1.054390748	1.613069829	1.357673747	1.731184495	0	1.605757622	2.630066154	1.785379754	5.075352407	26.80343432	C_{30}	

I: sustainable development index and F: Factors.

Table 13. Maximum score per SD criterion (worst case scenario) (SDMS) [own research].

Criteria	Sub-criteria	Score
Economic	Costs of health, safety, and environmental protection	67.66
	Production rate and productivity	77.92
	The hidden value of technology advances and insights	43.73
	Mine life	78.44
	Operation and capital cost	78.37
	Mineable ore tonnage	68.65
	Mineral value and income per ton of ore	78.28
	Mine closure (and reclamation) cost	78.21
	Dilution rate and ore loss rate	28.60
	Initial investment rate of returns	77.29
Environmental	Green mining (principle protection of resources and energy)	37.85
	Post-mining land use type	78.65
	Management of waste pollutants	48.95
	Use green space to help protect the environment	19.26
	HSEC management system	18.63
	Reduce pollution and environmental degradation	69.19
	Bed coordination (area ecosystem)	18.79
	Ground surface subsidence	59.70
	The principle of respect for the mining site	39.43
	Mine effluent management	26.99
Social	Increasing the employment rate of indigenous people	47.55
	Improve employee performance	57.66
	Skills training	56.02
	Health (safety and usefulness) for people inside the mine	39.85
	Infrastructure development	27.71
	Life expectancy	38.40
	Communication with local communities	38.39
	Other local community issues	49.17
	Revival of cultural and regional identity	66.86
	Considering the interests of the next generation and the present together	36.79

Table 14. The severity of the impact of the transition from open pit to underground mining on sustainable development criteria [own research].

Criteria	Sub-criteria	Score	Intensity of impact[a]
Economic (ERS)	Costs of health, safety, and environmental protection	67.66	high
	Production rate and productivity	77.92	very high
	The hidden value of technology advances and insights	43.73	medium
	Mine life	78.44	very high
	Operation and capital cost	78.37	very high
	Mineable ore tonnage	68.65	high
	Mineral value and income per ton of ore	78.28	very high
	Mine closure (and reclamation) cost	78.21	very high
	Dilution rate and ore loss rate	28.60	medium
	Initial investment rate of returns	77.29	very high
Environmental (EnRS)	Green mining (principle protection of resources and energy)	37.85	medium
	Post-mining land use type	78.65	very high
	Management of waste pollutants	48.95	medium
	Use green space to help protect the environment	19.26	low
	HSEC management system	18.63	low
	Reduce pollution and environmental degradation	69.19	high
	Bed coordination (area ecosystem)	18.79	low
	Ground surface subsidence	59.70	high
	The principle of respect for the mining site	39.43	medium
	Mine effluent management	26.99	medium
Social (SRS)	Increasing the employment rate of indigenous people	47.55	medium
	Improve employee performance	57.66	high
	Skills training	56.02	high
	Health (safety and usefulness) for people inside the mine	39.85	medium
	Infrastructure development	17.71	low
	Life expectancy	38.40	medium
	Communication with local communities	18.39	low
	Other local community issues	39.17	medium
	Revival of cultural and regional identity	26.86	medium
	Considering the interests of the next generation and the present together	36.79	medium

[a] (0–25 = low, 26–50 = medium, 51–75 = high and 76–100 = very high).

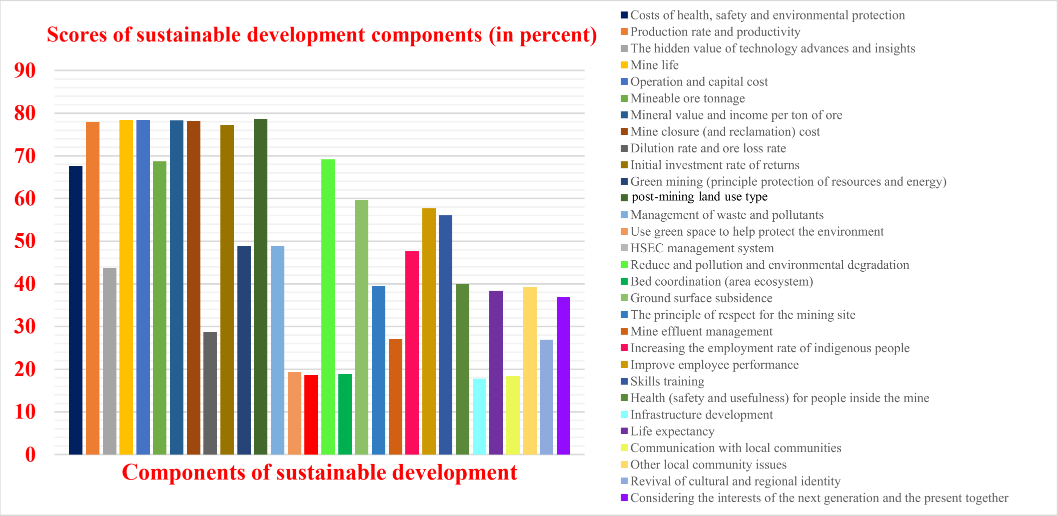

Fig. 3. The effects of transition from open pit to underground mining in Songun copper mine on each component of sustainable development [own research].

Considering the relative weight of the factors influencing the evaluation matrix, the maximum score of each sustainable development criterion (worst case) is different, and therefore, the scores of sustainable development criteria are not comparable. Therefore, by calculating the relative score of each criterion based on the maximum impact score, the real impact intensity is obtained. With this type of output from the evaluation matrix, the estimated power of impact on each development criterion can be compared to the maximum impact intensity. The elements in Table 14 indicate the severity of the impact on each sustainable development measure, and values close to 100 percent indicate severe consequences and adverse conditions.

The relative score of each sustainable development index that shows the overall impact of the transition operation on that index, based on the results of Table 14, according to equations (1)–(3), is equal to:

$$ERS = \frac{0.6715}{10} \times 100 = 67.72 \tag{1}$$

$$EnRS = \frac{0.4174}{10} \times 100 = 41.74 \tag{2}$$

$$SRS = \frac{0.3984}{10} \times 100 = 39.84 \tag{3}$$

In these relationships, *ERS*, *SRS*, and *EnRS* show the relative score of economic, social, and environmental indexes, respectively. To determine the overall impact of transition operation on the sustainable development index and to compare the results of the sustainable development assessment matrix, the final relative score or "relative overall impact score" is calculated according to equation (4).

$$\text{relative impacts of the score} = \frac{67.72 + 41.74 + 39.84}{3} = 49.76 \tag{4}$$

The impacts of the transition operations from open pit to underground mining in Songun copper mine on each component of the sustainable development index are shown in the bar chart in Fig. 3.

According to the bar chart in Fig. 3, the transition operation in the Songun copper mine has the most significant effect on components of production rate and productivity, mine life, operation and capital cost, mineral value and income per ton of ore, mine closure (and reclamation) cost, Initial investment rate of returns, post-mining land use type.

4. Conclusions

Given the necessity and importance of sustainable development in achieving a balanced society, the human endeavor is to use the infrastructure and resources to meet their needs to have the most negligible impact on future generations.

In metal deposits that have a significant slope and depth expansion, the mining of the deposit is first started with surface mining methods (mainly open pit). As the mine deepens, the ratio of the tonnage of tailings extracted per one ton of mineral material reaches such a level that mining by other surface methods has no economic, social or environmental justification. After this depth, if the reserve is suitable for volume and grade, extraction continues using underground methods. The most critical issue, in this case, is determining the "optimal transition depth from open pit mining to underground (OTD") [17].

Today, due to the increase in world population, increase in demand and consumption of minerals, the production of minerals has increased, and mines are located near urban and rural communities. It is necessary to extract minerals in these conditions in such a way as to cause the minor damage to the environment, local communities, and the economic prosperity of the mining area. According to the definition of sustainable development, determining the optimal transition depth without considering and calculating sustainable development indicators (economic, social, and environmental) is a non-scientific and non-optimal strategy.

Many instrumental studies have been carried out in evaluating the various effects of mining activity with a semi-quantitative combined approach and multi-criteria decision-making methods. The most critical weakness of these methods is that they are not comprehensive and do not consider the combined extraction mode. In addition, most of these researches have focused on open-pit mining and environmental impacts, and all three sectors of sustainable development, especially social sectors, have been less addressed.

Thus, in the presented research, to assess the environmental, economic, and, social impacts of the transition from open-pit to underground mining in the Songun copper mine, a matrix structure has been used, which incorporates the influential factors and the environmental, economic, and social components of the dimensions of this matrix. To determine the influential factors, the score of the influential factors, and the impact of the influential factors on the environmental, economic, and social components, expert opinions have been used. By quantifying the qualitative comments, the overall impact on environmental, economic, and social components was determined.

According to the evaluations and calculations made regarding the transition from open pit to underground mining in Songun copper mine, it was observed that the impact of the transition from open-pit to underground mining in this mine is high on all three indicators of sustainable development. According to the obtained results and the significant effects of this activity, the transition in the studied mine has fragile stability. Therefore, based on the percentage of damage on the various parts of the indicators, strategies should be made to predict and prevent adverse effects in this mine. According to the assessments, the transition operation in Songun copper mine has the most significant impact on components such as production rate and productivity, mine life, operation and capital cost, mineral value and income per ton of ore, mine closure (and reclamation) cost, Initial investment rate of returns, post-mining land use type.

Ethical statement

We state that the research was conducted according to ethical standards.

Funding body

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Conflict of interest

None.

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