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Approach to identifying sustainable development attributes effective in open pit mine design

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ABSTRACT

Mining design is a vital part of the mining life cycle, and the integration of sustainable development (SD) considerations makes the project a profitable activity with the least adverse social and environmental impacts. Applying sustainability considerations in the very late stages of project development and focusing on impact mitigation and control measures has been one of the most important reasons for not integrating the principles of SD in the feasibility and design stages of projects. In this study, the attributes of the three principles of SD discussed in various studies were collected, and a logical approach was adopted to identify the social and environmental details effective in the design, optimization, and selection of the ultimate pit limit (UPL). Then, political-security problems, creation of employment, pollution of underground/surface waters, acidic depositions, materials existed in the tailings dam, soil physical specifications, the recycling/removal of waste, restoring habitat post-mining, tailing dams and waste dumps and respect of sensitive areas were selected for quantification and integration in the sustainable design of the Sungun copper mine as a case study.

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1 .Introduction

Sustainable development (SD) results from an interconnected set of economic, social, and environmental activities (the three principles of SD) that meet many needs with proper long-term planning. This concept is, therefore, not a purely environmental one. It is a theory that emphasizes the economy and living conditions of the people before the environment. If SD standards are applied, on the one hand, resources are expected to be depleted later. On the other hand, new methods are developed with the advancement of technology that will maximize the benefits with minimal use of resources [1].

There is an interrelationship between this concept and mining that requires one to do the other. The mining industry is a source of foreign exchange income in many developing countries, and investment in this industry is mainly provided through foreign capital in the form of borrowing. Mining is the basis of the economic development of many of these countries, and the development of the mining sector has provided the best opportunity for their growth. This industry is closely related to sustainable development due to significant positive and negative effects on the environment, society, and the economy. On the one hand, the constraints of mineral resources, the possibility of their depletion, and the concerns about their scarcity for future generations, and on the other hand, the economic, social, and environmental problems caused by mining have led to the entry of SD in this industry as a need to protect natural, human and social capitals [2].

One of the first steps of extensive mining activity is mine design and planning and determining the ultimate pit limit (UPL). The objective function of this issue often has an economic aspect and is based on maximizing profit. Despite many studies in this area, there are still shortcomings that their consideration in the early stages of mine design, in addition to making the project more realistic, leads to maximizing the positive effects and minimizing the adverse social/environmental impacts, and even increasing the net present value (NPV) of the project as much as possible [3]. In this regard, SD is a relatively new concept that has entered the mining field in recent years, and developed countries are trying to adapt their mining operations to its principles. From the perspective of SD, not only is the economic aspect of the activities discussed, but also the other two fundamental principles, namely society and the environment, should be equally considered in mining. In other words, the selected UPL based on SD may differ from the selected UPL based on profit maximization. Therefore, it is necessary to provide a solution to integrate the social and environmental criteria of SD in the design of open pit mines and the selection of UPL in addition to economic cases.

Few studies have been conducted to integrate various sustainability criteria in mine design and planning. Muñoz et al. (2014) selected the optimal UPL by calculating some environmental and social components in the economic valuation of the blocks and incorporating them in the objective function as profit or cost. Energy consumption, greenhouse gas emissions, freshwater consumption, acid mine drainage generation, and direct employment generation were the only environmental and social components studied in this study [4].

Xu et al. (2014) included ecological costs as the only component of SD in ultimate pit optimization using a moving cone elimination algorithm. In this research, the environmental costs had lost value of direct eco-services (providing bio-products), lost value of indirect eco-services (soil erosion control, air pollutant absorption, oxygen release, rain runoff control, and soil nutrient formation), prevention and restoration costs, and the cost of carbon emission from energy consumption[5].

Moradi and Osanloo prioritized SD criteria affecting open pit mine design using a preference voting system (PVS) and data envelopment model (DEA). In this research, after identifying 77 attributes of SD, ecological costs and post-mining incomes were integrated into UPL design[6,7].

Adibi and Ataeepour (2015) developed a model to consider the economic and social benefits and minimize the negative environmental impacts of an open-pit mine during UPL design and before exploitation. SD parameters calculated were NPV or profit, post-mining income per year, taxes generated, indirect mining benefit (from an economic aspect), job security, safety, resource efficiency, number of employees (from a social aspect), and reclamation, land use, waste production, and energy consumption (from an environment aspect) [3]. In another study, Adibi et al. (2015) used the Technique for Order of

Preference by Similarity to Ideal Solution (TOPSIS) to find ranks of alternative UPLs after integrating quantitative criteria of SD in the UPL design.

TOPSIS is based on the concept that the chosen alternative should have the shortest geometric distance from the positive perfect solution and the longest geometric distance from the negative ideal solution[8].

Narrei and Ataee-pour (2020) used the "choice experiment (CE)" method for estimating the utility function and the value of effects caused by mining based on the principles of SD. The CE method exists as an application of the theory of Lancaster's characteristics approach. The theory of Lancaster's characteristics approach holds that the desirability of consuming a commodity can be subcategorized into the desirability obtained.

2. SD criteria

2.1. Economic criterion

The effective economic attributes in sustainable mining that have been mentioned in various scientific sources are cut-off grade, mining capacity, reclamation method, access to new roads, access to water resources, machine/equipment capacity, geometric and geomechanical constraints, type of ore, price of product, cost of lost opportunities, costs associated with the creation of a stockpile, annual production rate of the mine, ability to execute the plan, risk, maximum expansion of ultimate pit limit, maximum potential of extractive reserves, surplus or shortage of mineral resources in comparison to domestic consumption [6], break-even point, internal rate of return, coordination to regional economic condition, authority of reclamation project execution, executive managing experiences availability, required machines, and equipment availability, need for specialist workforces, reclamation techniques availability, budget providing

potential, regional potential for implementation the new land use [10, 11], reduce waste, reuse of waste, long term asset value [12], topography of mine area, pit geometry, capital costs, operational costs, monitoring costs, maintenance costs, increase in income of local community (contribution to local economy), increase in governmental incomes, potential of investment absorption, positive changes in real estate value [10-15], extractive reserves, resource productivity [6, 16], structural/engineering geology, and hydrogeological conditions [6, 17], use of resources and availability [12-14, 18, 19], process recovery [20, 21], dump size [22], chemical loss, energy cost, closure cost [23, 24], slop stability [25, 26], the cost of carbon emissions from energy use, lost value of indirect ecological services, ecological or environmental costs associated with damaged or damaged forests [5], management cost of acid mine drainage, product income, cost of fresh water [4, 27], shareholder value, value added [13, 19], location of mined lands, costs per job [28], pre mining land value, post mining land value [22, 28], total restoration costs [5, 13, 18, 19, 29], post mining incomes (land use) [13, 18-20, 28- 31], taxes [28, 30, 32], public expenditure on education [15], maximize net return [33], economic efficiency [34], contribution to GDP and wealth creation [13, 18-20, 28], maximum potential of product consumption in domestic and foreign markets [28, 35, 36], maximum production capacity in mine [6, 37] and mine life [6, 38].

2.2. Social criterion

The social attributes of SD discussed in scientific references are stakeholder associations, mining from the local people's point of view, type of cultural texture of the region people, legislative frameworks, political-security problems, productivity index in the community, participation of NGOs, designation of income to local communities, urban development, income from the reduction of social anomalies, attraction potential of investors in the mining sector, life satisfaction, increasing the level of knowledge and culture of the region people, rate reduction of social anomalies, preparedness for unforeseen events, increase of public trust, responsibility, the number ratio of young to old people in the community [6], community identity, strength of local and regional institutions for planning and governance [14], migration, mining city survival [28], planning for mine closure, resettlement [16, 35, 36], displacement and loss of land, stakeholder involvement, destruction of traditional forms of livelihoods, degradation of social customs [19, 39], labor relations, recognition of local communities' concerns, occupational illness, working conditions (audible/visual environment) [34], life expectancy of persons aged 65, infant deaths [15], community participation [6, 14, 16], consistency with the development plan of the local community, bribery and corruption,

equity/income distribution/equal opportunities and non-discrimination, labor/management relationship [13, 19, 35], creation of employment, demographic changes [14, 38, 40-41], public policy [35], employment of local work force, labor availability [11, 14, 19, 43], property values [12], land ownership [16, 28], economy of the community and wage level [13, 18, 19, 28], decrease of unemployment rate [15, 33, 44], training and education [30, 33, 35, 36, 45], quality of life [28], employee education and skills development [16, 18, 19], human rights and business ethics [19, 32], historical and cultural heritage [34, 37, 38, 42], avoidance of child labor [33], housing, welfare facilities and improving infrastructures [25, 30, 38], and health, safety and security [12, 16, 26, 30].

2.3. Environmental criterion

The most important of these attributes are pollution of underground waters, pollution of surface waters, traffic, explosives [12, 29, 38, 42], soil physical specifications, soil chemical specifications [10, 11], ecosystem destruction, ecosystem alteration [23, 28], acidic depositions, oil and fuel spills [10], pre-mining environmental conditions, adaptation to the environment, improving environmental standards, early closure of the mine [6], climate of the area [14, 15, 46], exposition/visibility of the plant & tailing dump/dam [42], type and amount of waste produced, extend life of reserve [21], preserving of local species, possible contamination in future [28], environmental conditions after mining/land degradation, restore habitat post mining, efficient use of natural resources [37], wildlife habitat quality, respect of sensitive areas [34], vegetation coverage and habitat destruction/degradation, disturbance of fauna [29, 42], lock-up of large areas of fertile land under waste dump, sedimentation of rivers and flooding in nearby villages [19, 39], materials existed in the tailings dam, materials existed in the waste dump, aesthetics, light [40, 41, 47], tailing discharge considerations/methods, exposition/visibility of the pit & mining area, noise pollution, fly-rock, ground vibration, instability of the established spaces, landform changes (subsidence) [40, 42, 47], global warming, tailings dams & waste dumps, reduce energy consumption [13, 18, 19], erosion & landslides (soil instability) [10, 16], the recycle/removal of waste [18, 20, 21, 24, 28], forestation every year [20], water resources depletion [23], land occupation [17], and open pit voids [25].

3. Results and discussion

3.1. Criteria ranking

To assess the criteria of the three principles of SD affecting the design, optimization, and selection of the UPL, 49 environmental attributes, 73 economic attributes, and 56 social attributes were identified. By designing a questionnaire, these attributes were evaluated by 25 international experts from developed countries in terms of their importance in calculating the economic value of the block. The final score of each feature was calculated from the average of the values given by experts (1=very little importance to 5 very high priority). Then, their thematic and attribute ranking was done based on the results.

3.1.1. Thematic ranking

Table 1 shows the thematic order of the attributes and the final score of the principles. According to this table, there is no significant difference between the scores of the three principles of SD, which means the importance of integrating social and environmental criteria in the design, optimization, and selection of the UPL. Water quality, with a rank of 2, and socio-economic, with a level of 9, were identified as the most influential environmental and social themes, respectively.

Table 1. Thematic ranking of attributes and determining the value of the criteria of SD.

SD principles	Principle score	Theme	Theme score	Rank
Environmental	3.532	Water quality	4.06	2
		Air quality	2.75	14
		Soil quality	3.66	5
		Landscape	3.247	11
		Biodiversity	3.72	4
		Side-effects of mining	3.497	8
Economic	3.684	Technical considerations	3.767	3
		Economic considerations	3.625	6
		Executive consideration	3.512	7
		Production and consumption of the product	4.013	1
Social	3.285	Social-political	3.371	10
		Social-economic	3.471	9
		Social-cultural	3.152	12
		Workforce health	3.137	13

3.1.2. Attribute ranking

The attribute ranking of criteria with high/very high importance (score ≥ 4) is shown in Table 2. According to this table, the integration of social attributes of health, safety and security, political-security problems, creation of employment, attraction potential of investors in the mining sector, and legislative frameworks, and environmental attributes of pollution of surface waters, water resources depletion, efficient use of natural resources, environmental conditions after mining/land degradation and type and amount of waste produced are critical in the design, optimization, and selection of the UPL. Table 3 shows 24 attributes of low/very low importance that were removed from the evaluation process.

3.2. Case study

Since the geographic location of the mines can affect the importance of SD criteria, the Songun copper mine was selected as a case study. A questionnaire consisting of the remaining 154 attributes (score≥3) was surveyed by experts from the mining design office, and a similar approach was used for the ranking process. The results of the thematic ranking of attributes are presented in Table 4.

A comparison of the opinions of mining experts (Table 4) and international experts (Table 1) shows that both groups agreed on the top 5 priorities of themes. Production and consumption of the product, water quality, technical considerations, biodiversity, and soil quality were selected as priorities 1 to 5 of the ranking process of themes, respectively. Another critical point in the comparative evaluation of Tables 1 and 4 is the more noticeable difference in the scores of the principles of SD. Mining experts considered less critical for social and environmental criteria than economic ones. This result can be attributed to the difference in the views of experts from developed and developing countries on integrating SD considerations in mining.

Table 5 shows the ranking of the high/very high importance (score ≥ 4) attributes. According to this table, political-security problems and creation of employment as social attributes and pollution of underground waters, the recycling/removal of waste, pollution of surface waters, acidic depositions, materials existed in the tailings dam, soil physical specifications, restoring habitat post-mining, tailings dams & waste dumps and respect of sensitive areas as environmental attributes can be very effective in the design, optimization, and selection of the UPL. A comparison of Tables 2 and 5 shows the political-security problems, creation of employment, and pollution of surface waters are the only common attributes selected by international and mining experts. Regardless of the differences in the views of experts, this is due to the social consequences and especially the environmental problems of mining, which are primarily dependent on the geographic location of the mine.

Table 2. Ranking of high/very high-importance attributes.

SD criteria	Attribute	Score	Rank
Economic	Cut-off grade	4.68	1
	Price of product	4.64	2
	product income	4.64	
	Extractive reserves	4.56	3
	Capital costs	4.48	4
	Operational costs	4.48	
	Internal rate of return	4.48	
	Geometric and geomechanical constraints	4.44	5
	Slope stability	4.44	
	Break-even point	4.36	6
	Annual production rate of the mine	4.32	7
	The maximum expansion of ultimate pit limit	4.32	
	Economic efficiency	4.28	8
Social	Health, safety, and Security	4.24	9
Environmental	Pollution of surface waters	4.2	10
Economic	Structural/Engineering geology and hydrogeological conditions	4.16	11
Environmental	Water resources depletion	4.12	12
Economic	Maximize net return	4.12	12
	The management cost of acid mine drainage	4.08	13
	The maximum potential of product consumption in domestic and foreign markets	4.08	
	Maximum production capacity in the mine	4.08	
	The maximum potential of extractive reserves	4.08	
Social	Political-security problems	4.08	13
	Creation of employment	4.08	
Environmental	Efficient use of natural resources	4.04	14
Economic	Mine life	4.04	14
Social	Attraction potential of investors in the mining sector	4.04	14
Environmental	Environmental conditions after mining / Land degradation	4	15
	Type and amount of waste produced	4	
Economic	Mining capacity	4	15
	Type of ore	4	
Social	Legislative frameworks	4	15

Table 3. Low/shallow importance attributes.

SD criteria	criterion score	Theme	Theme score	Rank
Environmental	3.410	Water quality	4.2	2
		Air quality	3.4	7
		Soil quality	3.475	5
		Landscape	3.467	6
		Biodiversity	3.482	4
		Side-effects of mining	3.091	10
Economic	3.732	Technical considerations	4.09	3
		Economic considerations	3.525	8
		Executive consideration	3.3	9
		Production and consumption of the product	4.367	1
Social	2.986	Social-political	3.055	12
		Social-economic	3.062	11
		Social-cultural	2.918	13
		Workforce health	2.8	14

Table 5. High/very high importance attributes in the case study.

SD criteria	Attribute	Score	Rank
Economic	Extractive reserves	5	1
	Cut-off grade	5	
	Structural/Engineering geology and hydrogeological conditions	5	
	Slope stability	4.8	2
	Price of product	4.8	
	product income	4.8	
	Break-even point	4.8	
	Mine life	4.8	
	Machine/equipment Capacity	4.6	3
	Pit geometry	4.6	
	Capital costs	4.6	
	Operational costs	4.6	
	Maximum production capacity in the mine	4.6	
	The maximum expansion of ultimate pit limit	4.6	
Environmental	Pollution of underground waters	4.4	4
Economic	Mining capacity	4.4	4
	Topography of mine area	4.4	
	Internal rate of return	4.4	
	Required machines and equipment availability	4.4	
	The maximum potential of extractive reserves	4.4	
Environmental	The recycling/removal of waste	4.2	5
Economic	Type of ore	4.2	5
	Dump size	4.2	
	Maximize net return	4.2	
Environmental	Pollution of surface waters	4	6
	Acidic depositions	4	
	Materials existed in the tailings dam	4	
	Soil physical specifications	4	
	Restore habitat post-mining	4	
	Tailings dams & waste dumps	4	
	Respect for sensitive areas	4	
Economic	Access to water resources	4	6
	Geometric and geomechanical constraints	4	
	Process recovery	4	
	Annual production rate of the mine	4	
	Economic efficiency	4	
	Surplus or shortage of mineral resources in comparison to domestic consumption	4	
Social	Political-security problems	4	6
	Creation of employment	4	

4. Conclusions

To date, the standard foundations for resource evaluation and mine design and planning have not made any significant progress in integrating the concepts of SD. The best available economic and engineering evaluation methods used by the mining industry in the feasibility and design stages of the project do not consider the sustainability principles. The main reasons for not integrating SD issues in these stages are:

- Sustainability considerations are applied in the final stages of projects when most aspects affecting socio-environmental issues have already been decided.
- Sustainability considerations mainly focus on mitigation effects and control measures that are evaluated outside the scope of mine design and operational planning processes.

Integrating sustainability during mine design and planning is expected to be a cost-effective way to reduce social and environmental risks and increase opportunities in the mining life cycle and beyond.

This research can be the first step to integrating effective social and environmental criteria in mine design. At this step, an attempt has been made to introduce a logical approach to selecting the best SD attributes for each case study through comprehensive studies and collecting the most discussed attributes and surveys of experts active in this field. Mining designers can base production planning on the critical principles of SD, using these attributes in determining UPL. In this regard, the researchers' future research is focused on quantifying selected critical characteristics in a case study with the choice experiment method.

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Ethical Considerations

The authors avoided data fabrication, falsification, and plagiarism, and any form of misconduct.

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Conflict of Interest

The authors declare no conflict of interest.

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