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Assessing Optimal Open-Pit Orientation Strategies in the Development Phase of Copper Mining: Environmentally Sustainable Approach

*** Mohammad Jawad Jahed[1], Mohammad Fahim Weyaar[2], Aref Naimzad[3]**

[1]Graduate Student, Afghan International Islamic University, Engineering Faculty, Mining Engineering and Management Department, Kabul, Afghanistan

[2]Assisstant Professor, Afghan International Islamic University, Engineering Faculty, Mining Engineering and Management Department, Kabul, Afghanistan

[3]Associate Professor, Afghan International Islamic University, Engineering Faculty, Industrial Engineering Department, Kabul, Afghanistan

Abstract

The article aims to select the optimal orientation for open-pit mining at the Aynak copper deposit in the central zone of Afghanistan. The one used is the one that studied integrates geological and environmental datasets derived from over 100 samples analyzed by the United States Geological Survey (USGS), the former Soviet Geological Survey, and the Afghanistan Ministry of Mining and Petroleum. The software used for analysis is QGIS, and AutoCAD is used. This research aims to determine the optimal orientation and design configuration for open-pit extraction during the Aynak project's developmental stage. The result demonstrated that the deposit percentage varies from 0.5 to 2.3 percent. Total ore tonnage is 368 Mt, average grade is 1.7 percent, and metal tonnage is 6 Mt. As a result, the best orientation method is from side to center (from the western side to the eastern side).

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Introduction

Ore is a natural aggregate of one or more solid minerals that can be mined, or from which one or more mineral products can be extracted at a profit (USGS, 2016). This paper aims to identify and select the most appropriate orientation methods for the Aynak copper deposit from an environmental perspective. The study seeks to determine which orientation method is most suitable and how the mining operations should be developed to ensure efficient and sustainable extraction. This issue is a core challenge in developing the deposit.

Four internationally recognized orientation options are reviewed in this study, and the geological parameters of the ore have been collected and analyzed. Based on these assessments, the most effective orientation method is selected to guide the extraction process. The extraction

***Correspondence:** jahejwad@gmail.com

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method should be evaluated against many factors, including environmental, technical, economic, and safety considerations. By analyzing these factors, we can decide whether the ore should be extracted by open-pit mining, underground mining, or a combination of both (Hartman, 2002). Open-pit mining is the process of extracting ore near the earth's surface by removing the topsoil, vegetation, and overburden of waste rock, which can significantly impact the environment. Therefore, it is fundamental to manage mining extraction using sustainable methods, modern technology, and practices that minimize environmental destruction.

Ore extraction requires several stages, including prefeasibility, feasibility, exploration, development, exploitation, mineral processing, and rehabilitation (OceanaGold). In this article, the focus will be on the development stage—specifically, determining the starting point of extraction (i.e., from which side extraction should begin) and its impact on the environment. The choice of the starting point depends on many factors, such as ore depth, geological conditions, ore grade, stripping ratio, extraction orientation, safety considerations, and environmental assessment (Poblete et al., 2016).

The mining area under consideration is the Aynak copper deposit, located in Logar Province, Afghanistan (Benham et al., 2024). This mineralization consists of a silicified, limonite-bearing zone 4,000 to 5,000 meters long and 300 to 400 meters wide, composed of deformed and faulted rock. It contains at least four areas with extensive malachite, azurite, pyrite, disseminated chalcopyrite, bornite, and galena, with copper grades ranging from 0.25% to 1.34% (Shafai et al., 2021).

Sustainable extraction is especially fundamental in mining engineering, particularly for large-scale open-pit mining. The focus should be on ensuring mining safety, managing waste, and minimizing overburden removal to reduce environmental degradation. Currently, the development of reserves in steeply dipping ore deposits by the open-pit method is carried out to final depths of up to 800 meters. However, the economic indicators of a mining and technical system (MTS) deteriorate as the depth of the open pit increases. An MTS is composed of multiple subsystems, with the greatest costs arising from open-pit transport operations. For example, transporting the rock mass can account for 60–70% of total costs, while creating an opening scheme and equipping it with trucks can account for 30–50% of the costs of opening. Ensuring the sustainability of MTS operations is therefore a priority for mining enterprises (MEs), especially amid unstable external conditions and increasingly challenging mining environments (Rakhmangulov et al., 2021).

The newly published articles on the central part of the Aynak Copper deposit have been released since 2016. The results show that the central part of the deposit is extracted using open-pit mining methods. Based on this, some research has been conducted, particularly feasibility studies of the deposit. These technical and feasibility studies have suggested open-pit mining as the extraction method; however, no further research has been found regarding this mining approach. In addition, the Metallurgical Corporation of China (MCC) has not shared more detailed information about the deposit beyond geological conditions. Furthermore, the biggest problems were the archaeological constraints (due to Mes Aynak's status as a major

Buddhist heritage site) and security concerns, which further complicate decisions on extraction orientation and expansion paths.

Consequently, the main objective of this research is to analyze and determine the optimal orientation of mining operations during the development stage of the open-pit method in the central part of the Aynak Copper Deposit. The goal is to enhance ore extraction, minimize environmental degradation, and support environmentally friendly extraction in Afghanistan. To evaluate different orientation scenarios during the development stage of open-pit mining, this study will assess the impact of mining orientation on haulage distance and environmental constraints, and ultimately recommend the most efficient and sustainable orientation approach for initial mine development in open-pit mining.

Methods and Materials

This research focuses on analyzing and interpreting geological and operational data from the central part of the Aynak copper deposit to identify the most appropriate and sustainable orientation methods for the development stage of open-pit mining in this area. The methodology consists of several phases. The literature review has been conducted by examining geological information and data collected from several hundred boreholes, nine adits, and exploration records provided by the Metallurgical Corporation of China (MCC). In addition, globally recognized mining methods currently applied in copper deposits, as well as sustainable mining laws and regulations, have been reviewed and considered. The primary aim of this research is to investigate appropriate and sustainable orientations during the development stage of mining extraction. To achieve this, relevant formulas, techniques, calculation methods, and multi-criteria decision-making approaches will be employed in order to determine the most suitable orientation. The evaluation of orientations will be based on two principal factors: environmental and technical.

Two alternative orientation methods will be compared: (i) development advancing from the sides toward the center, and (ii) development progressing from the center outward to both sides. A comparative analysis of these alternatives against the two factors will identify the optimal option.

For spatial analysis and visualization of geological and environmental data, geographic information systems (GIS) tools will be used. Geological and mining parameters, such as ore tonnage, width and length of the ore body, volume of overburden, and rock characteristics, are evaluated at this stage to assess the orientation methods for the mining operation. Computer-aided design (AutoCAD) is used to draw schematic maps and visualize the ore body and pit design. The technical and economic analysis will focus on selecting the best option for the order of mining development, operational efficiency, environmental implications, waste management, and land disturbance. Based on the analyzed data, various mining orientation strategies (e.g., pit design direction, waste management, haul road placement) will be evaluated to minimize land disturbance, control waste disposal, and preserve ecological balance.

Operational safety and decision-support tools, along with comparative analysis techniques, will be used to rank orientation options based on predefined performance indicators.

Study Area

The Aynak Copper Mine is located across southern Kabul and northern Logar provinces. The main Aynak area spans approximately 3,439.37 square kilometers and includes five subareas; for more information, see Figure 1. According to geological reports, the copper deposit at Aynak is hosted within the Aynak Syncline Zone, which lies south of the Kabul Anticline. This zone stretches east-west, measuring about 60 kilometers in length and up to 20 kilometers in width. The deposit contains an estimated 240 million metric tons of ore, with an average copper grade of 2.3 percent (Taylor et al., 2011).

Figure 1: *Location of Aynak Copper Deposit (Taylor et al., 2011).*

Findings and Discussion

Demographic Characteristics

The Aynak copper deposit was formed through fluid mixing within permeable sedimentary and volcanic rocks. These sediment-hosted copper deposits typically occur within a narrow range of layers within a sedimentary sequence, and this study focuses specifically on Central Aynak. Geological investigations at Aynak were conducted in two phases between 1974 and 1989. These studies identified two main types of ore in the region, shown in Figure 2, which presents the geological map and cross-section of the Aynak deposit, highlighting its different geological categories and structural characteristics. The primary orebody consists of bornite, while chalcopyrite occurs both above and below this main ore zone. The upper portion of the orebody is hosted in carbonaceous quartz-sericite-biotite schists, sandstones, and breccias, containing minerals such as chalcopyrite, pyrite, sphalerite, and molybdenite. The lower portion lies within carbonaceous quartz-dolomite schists with breccia and includes chalcopyrite and pyrrhotite. According to geological studies conducted by the Metallurgical Corporation of

China (MCC), the copper resources in Central Aynak are classified into economic and sub-economic categories. The illustration is in Figure 2.

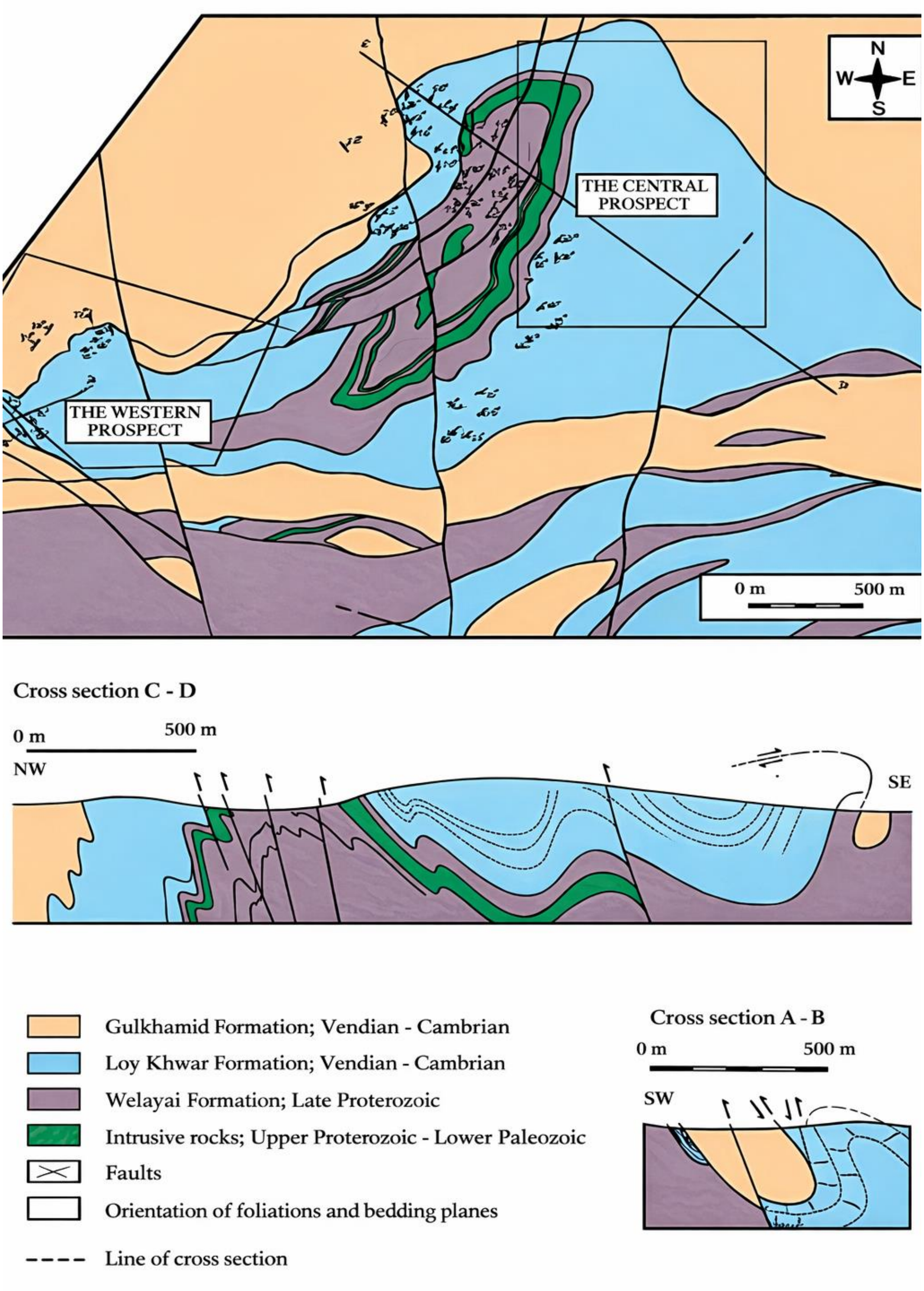

Figure 2: *Geological map and cross-section of Aynak Deposit categories (Noorhan, 2017).*

The central part of the Aynak copper deposit consists of three types of mineralization: sulfide, oxide, and a mixed sulfide–oxide zone. The corresponding numerical values are presented in Table 1 below.

Table 1: *Aynak copper deposit, central economic resource (Shafayi et al., 2022)*

Ore Type	Ore Tonnage (MT)	Cu Grade (%)	Cu Metal Tonnage (MT)
Sulfide	177	2.36	4.177
Mixed sulfide and oxide	7.3	2.5	0.185
Total	185	2.37	4.385

(Shafayi et al., 2022)

Furthermore, the Aynak copper deposit includes sub-economic resources, with varying copper quantities. Despite this variation, all of these resources are considered economically extractable. Detailed information is provided in Table 2.

Table 2: *Aynak copper deposit, central sub-economic resource*

Ore Type	Ore Tonnage (MT)	Cu Grade (%)	Cu Metal Tonnage (MT)
Sulfide	151	0.82	1.24
Mixed sulfide and oxide	11	1.03	0.11
Oxide	21	1.47	0.31
Total	183	1.1	1.67

(Shafayi et al., 2022)

Table 3 presents the total combined economic and sub-economic resources. The total copper ore is approximately 368 million tonnes, while the copper metal content is about 6 million tonnes.

Table 3: *Aynak copper deposit, central, Total economic resource*

Ore Type	Ore Tonnage (MT)	Cu Grade (%)	Cu Metal Tonnage (MT)
Sulfide	328	1.67	5.4
Mixed sulfide and oxide	18.3	1.8	0.33
Oxide	21	1.47	0.33
Total	368	1.7	6

(Shafayi et al., 2022)

Block modeling is used to define the volume of an ore deposit, set the boundaries for estimation, and ultimately calculate the ore reserves. When the ore body shows high variability, smaller blocks are necessary to reflect its changes in detail. Conversely, for ore bodies with lower variability, larger blocks may be sufficient. Choosing a block size that is too large or too small can lead to averaging effects that fail to represent the true grade distribution within the deposit. Therefore, the block dimensions are selected based on several key factors, including drill hole spacing, the mining method (such as bench height), and the geological characteristics of the ore deposit. At the Aynak copper deposit, the spacing between boreholes ranges from 20 meters to 100 meters, depending on the area. The ore body has a dip angle of approximately 30 degrees, and additional information on block model parameters is provided in Table 4 (Shafayi et al., 2022).

Block Model Parameters in Aynak Copper Deposit

Table 4 and Figure 3 below illustrate the modification of ore deposit boundaries using the Inverse Kriging (IK) and Sequential Indicator Simulation (SIS) methods. The yellow color represents copper grade distribution, whereas the red color indicates waste material. The X-axis denotes the width of the ore body, the Y-axis represents the length of the ore body, and the Z-axis corresponds to the elevation of the ore body.

Table 4: *Model parameters in Aynak copper deposit*

Type	X	Y	Z
Minimum	27808	91215	1486
Maximum	29248	93335	2496
Main-block size	10	10	10
Sub-block size	2.5	2.5	2.5

(Shafayi et al., 2022)

Figure 3 below illustrates the orientation of the ore body, based on the data provided in Table 4 above, and also shows its height, length, and elevation.

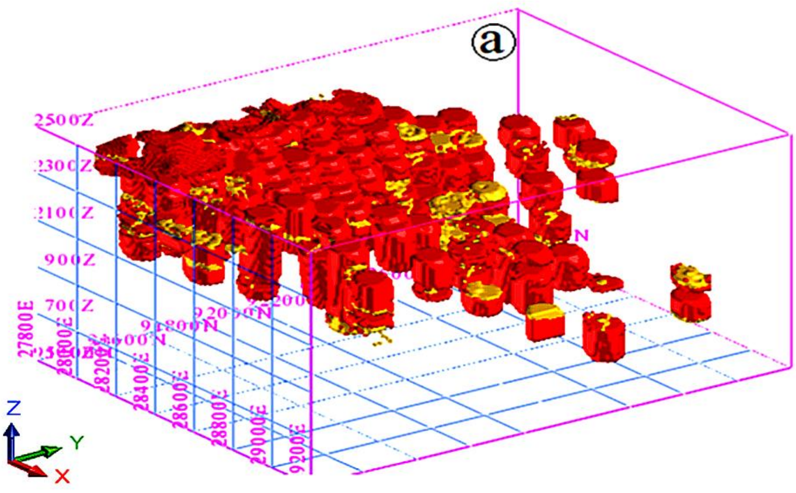

***Figure 3:** Model of the central part of the Aynak copper deposit (Shafayi et al., 2022).*

Reliability of Geological Information

The geological data concerning the Aynak copper deposit, as discussed above, are derived from scholarly articles and official publications of the Ministry of Mines and Petroleum of Afghanistan, with all references appropriately cited. The world, across all fields, depends entirely on mineral resource extraction (Cao et al., 2023). Illegal and less effective extraction of mineral resources has a huge impact on the environment, destroying soil, water, air, the environment, landscape, vegetation, and society (Little et al., 2016).

The design of mineral deposit extraction plays a critical role in ensuring both operational efficiency and environmental sustainability. The depth, dimensions, ore grade, ore type, and overburden size are important parameters for determining the orientation of mining and sustainable extraction. The 1000 m depth will be mined using the open pit method, transporting and then removing rock as necessary to determine orientation and ensure sustainable mining

(Rakhmangulov et al., 2022). The Aynak copper deposit, one of the largest deposits in Afghanistan, exemplifies the importance of this process; its resource is 240 million tons at a grade of 2.3% copper (Cu) (Waizy et al., 2020). Its extraction is expected to have significant environmental impacts; however, by selecting an optimal site and extraction method, these negative effects can be mitigated. Metals, such as copper, zinc, and lithium, are in need of new low-carbon release technologies, climate change mitigation, and adaptation to climate change impacts (Reyes et al., 2025). Copper is an industrial element, and its extraction requires technical processes and has a significant negative impact on the areas where it is mined. Using GIS and remote sensing analyses, we can identify the affected areas and choose alternative mining methods to turn the negative into a positive impact (Gunawardhana et al., 2025). The order of development of opencast mining work cannot be established arbitrarily. It depends, first of all, on the kind of deposit to be mined, surface relief, shape of the deposit, position of the deposit relative to the prevailing surface level, angle of dip, capacity, structure, quality distribution of minerals, and kind of overburden rock. The next logical consequence is the choice of opencast mining method: surface, deep, on-slope, on-slope-deep, or underwater. It is also essential to establish the points of location of consumers of the mined mineral, waste dumps, tailing dumps, and their approximate capacities, which will make it possible to outline the probable directions and ways of transportation of pit loads. Based on this reasoning, the probable dimensions of the open-pit field, its position in conformity with the surface relief, and the approximate contours of the mining can be selected. Only after that, and considering the planned capacity of the quarry, can one start working out the order of development of mining work within the limits of a given open-pit field; as a result, the schematic plan is shown in Figure 4.

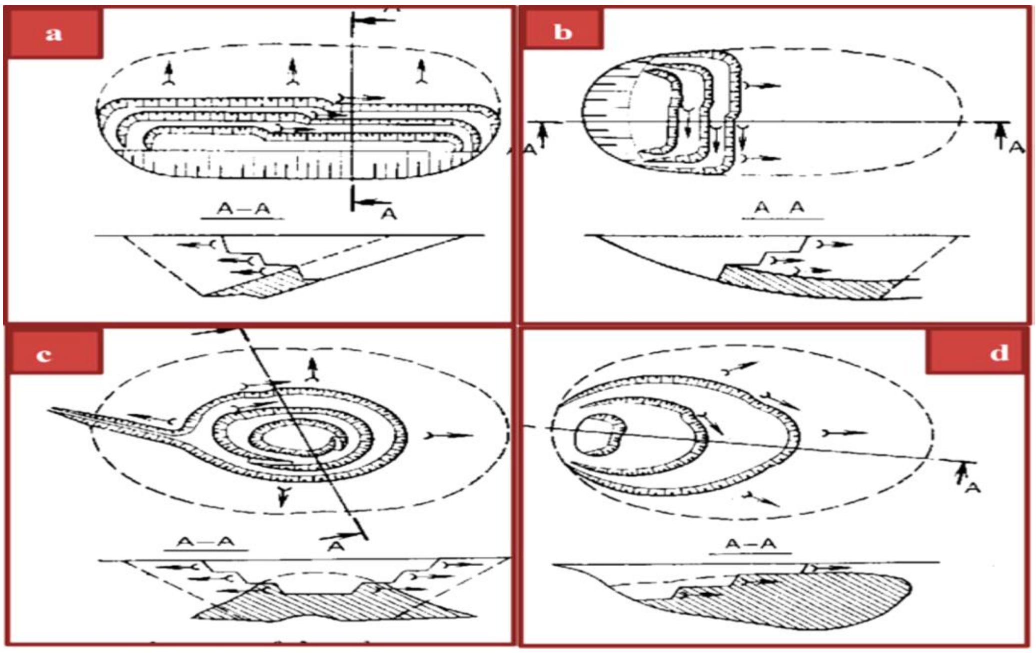

Figure 4:*Mining work development ((a) mining oriented along the longer axis of quarry, (b) along the shorter axis, (c) concentric mining line, (d) elliptical mining line) (Elbeblawi et al., 2020).*

Exploration data, however, do not clearly indicate which orientation would minimize environmental effects. On the other hand, details on the amount of resources are provided in

Table 1. Moreover, the geological map at a scale of 1:5000 is drawn; according to this map, a 3D model of the ore body position is demonstrated. The 50 m block Cu blocks >50th. percentile in yellow, >75th percentile in orange and >90th percentile in purple the 3D is mentioned in Figure 5.

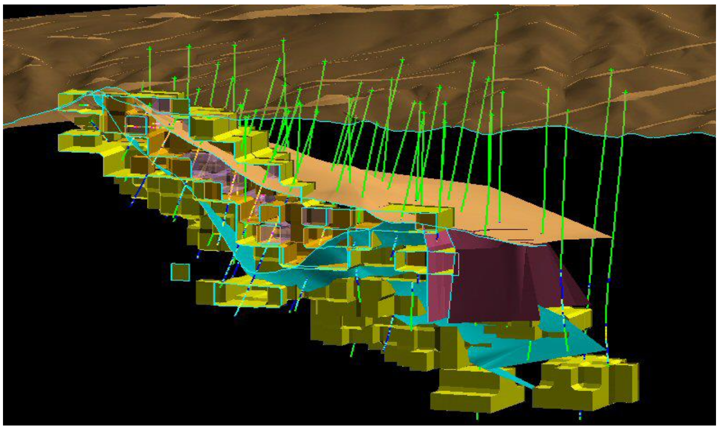

Figure 5: *3D Map Of Central Aynak Copper Deposit (BGS et al., 2005)*

Given the large-scale nature of the Aynak copper deposit, the environmental consequences are expected to be substantial. Nevertheless, sustainable extraction strategies can help reduce these impacts. A crucial step in this process is identifying the most suitable mining orientation. To support this decision, a Digital Elevation Model (DEM) was generated using Google Earth software and is clearly shown in the contour data, which were obtained from the United States Geological Survey (USGS) open topography.

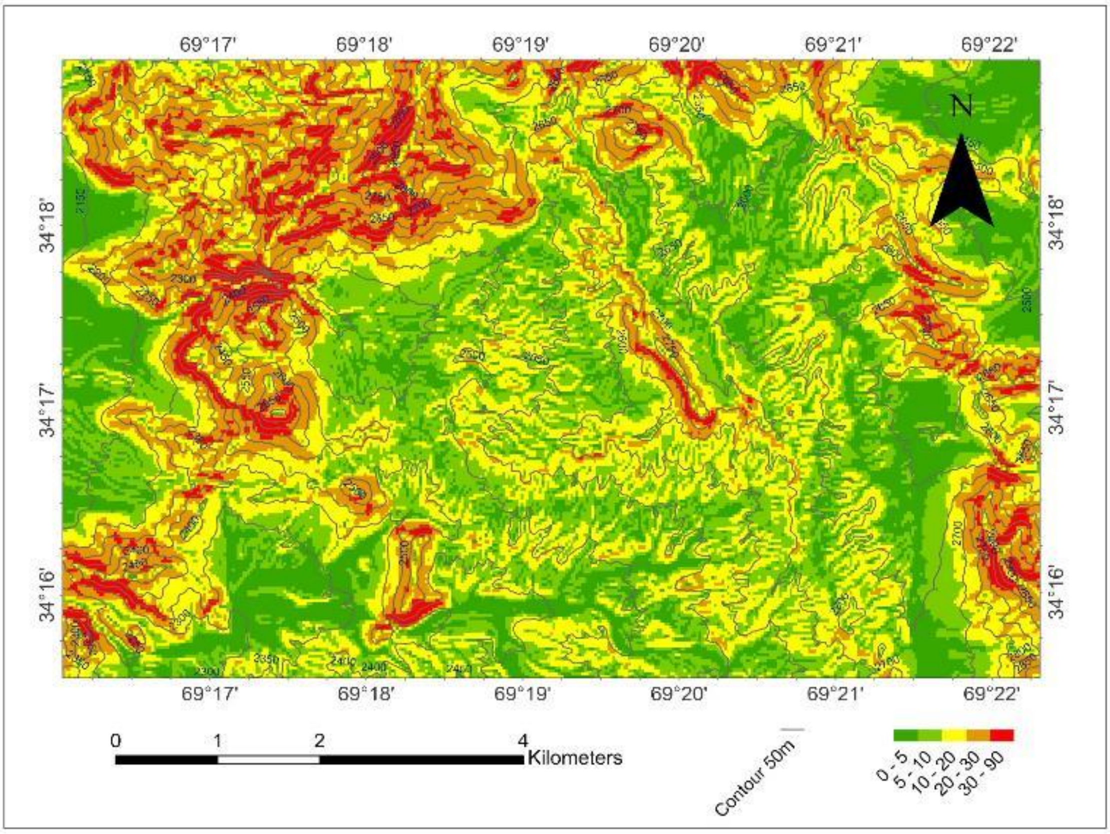

Figure 6: *Digital Elevation Model (DEM) of the Central Part of Aynak Copper Deposit.*

According to Figure 4, sub-figure (b) (mining oriented along to shorter axis) which is called in this article is option A that is oriented from side to center and and in Figure 4, sub-figure (c) which is called in this article option B (mining oriented along to concentric line) that is oriented from center to both sides, are analyzed, as a result the best option is the option A chosen for mining orientation in development stage of open pit mining. Orientation from side to center for this mining method, which offers more advantages from environmental and sustainable development perspectives: the less area removed by mining extraction, the more advantageous it is (Baek et al., 2017). This orientation also helps minimize environmental impacts by reducing disturbance to both surface and groundwater (Mensah et al., 2015), particularly when the deposit lies close to the surface. Furthermore, it requires less land for waste dumping, thereby limiting surface occupation. In addition, the side-to-center development pattern helps reduce overall destruction in the mined area within its boundary, ensuring disturbance remains more contained and manageable (Bowell et al., 2023). Adopting a side-to-center orientation also reduces transportation distances during the development stage. Shorter haulage requirements translate into lower energy consumption, which is environmentally advantageous. Reduced energy use not only minimizes greenhouse gas emissions but also contributes to lower levels of air and noise pollution, thereby lessening the overall ecological footprint of the mining operation (Rahimdel et al., 2025). In Figure 8 below, orientation from center to western and eastern side can offer environmental benefits such as greater slope stability, reduced and more evenly distributed haulage distances, optimized use of dumping space, better control of mine water, and concentrated disturbance zones that delay the impact on peripheral ecosystems (Baek et al., 2017).

Total Haulage: formula, each trip K = 1….. N, trips, Wk = Trips haul tonnes.

$$Q= \sum_{k=1}^{N\ trips} Wk \ldots.1$$

Total haul cast (energy/emission) across the pit; r, R be routes (origin-destination pairs), m, M materials (ore/waste), and $q_{m,r}$ the tonnes assigned to route r. Distance for loaded/empty legs is d_r^{ld}, d_r^{em}. Per-tonne-km variable cost (energy/emission factor) is K_m^{ld} K_m^{em}.

Total variable haul cost (energy/emissions) across the pit:

$$Ctotal\ \sum_{r}^{R}\sum_{m}^{M}\ q_{m,r}(k_m^{ld}d_r^{ld} + k_m^{em}d_r^{em}) \ldots..2$$

Schematic cross-section and plan views of the open-pit mine for both options have been drawn. These datasets were then integrated and analyzed using AutoCAD drawing tools and QGIS software to evaluate potential extraction sites.

Aynak Central Part Deposit Geological Parameters

The central part of the Aynak copper deposit exhibits the following geological characteristics. The strike of the ore body extends approximately 1,850 meters, while the down-dip length reaches about 1,200 meters, and the thickness is about 210 meters. The deposit dips toward the southeast at an angle ranging from 45° to 70°. The economic cut-off grade for copper mineralization in this section of the deposit is estimated at 0.4% Cu (Shafai et al., 2021).

Overburden Removal

Overburden removal is a fundamental issue in mining extraction (Jiskani, 2017). It is also influenced by the selected exploitation method, as well as by environmental, safety, and economic considerations that govern the feasibility and sustainability of mining operations (Oggeri et al., 2019). Overburden removal cost formula (Shustov et al., 2020). Is the following in equation formula 2?

Figure 4 above presents the possible starting points and orientations for ore body extraction, illustrating two scenarios: extraction from the sides toward the center and from the center toward both sides. In this study, only two orientations are explained schematically: Figure 7 shows extraction from the eastern side toward the center (hereafter referred to as Option A), while Figure 8 illustrates extraction from the center toward both the eastern and western sides (hereafter referred to as Option B). Demonstrating an extraction orientation from the side toward the center, as indicated in Figure 4, sub-figure (b). In this scenario, ore extraction begins on the western side of the Aynak copper deposit and progresses toward the center, continuing until the end of the ore body (Figure 7).

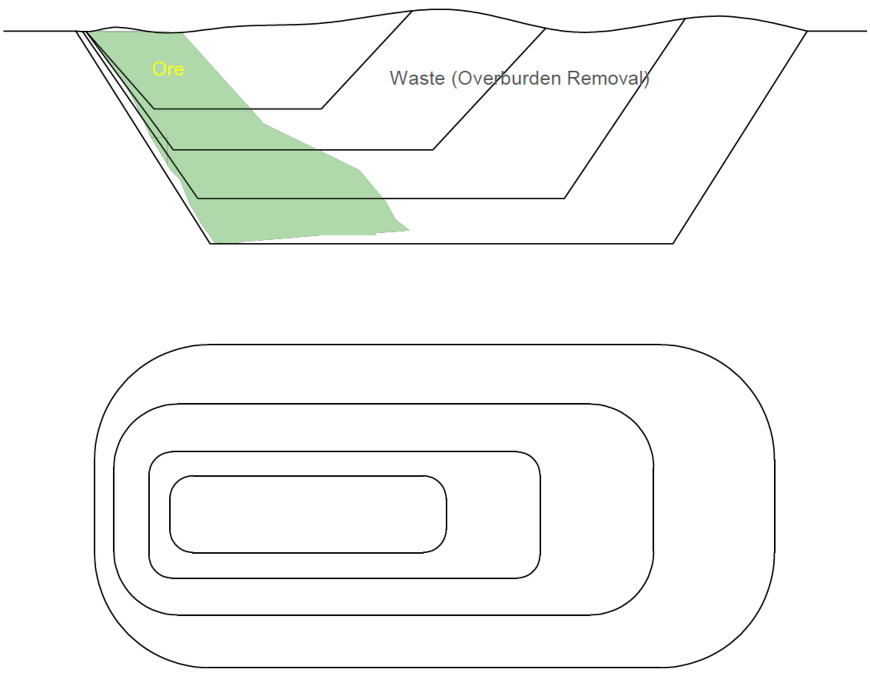

Figure 7: *Schematic view of cross-section and plan of option A*

Figure 8 below presents an extraction orientation from the center toward both sides, corresponding to Figure 4, sub-figure (c). In this case, extraction begins at the center of the deposit and extends outward toward both the eastern and western sides.

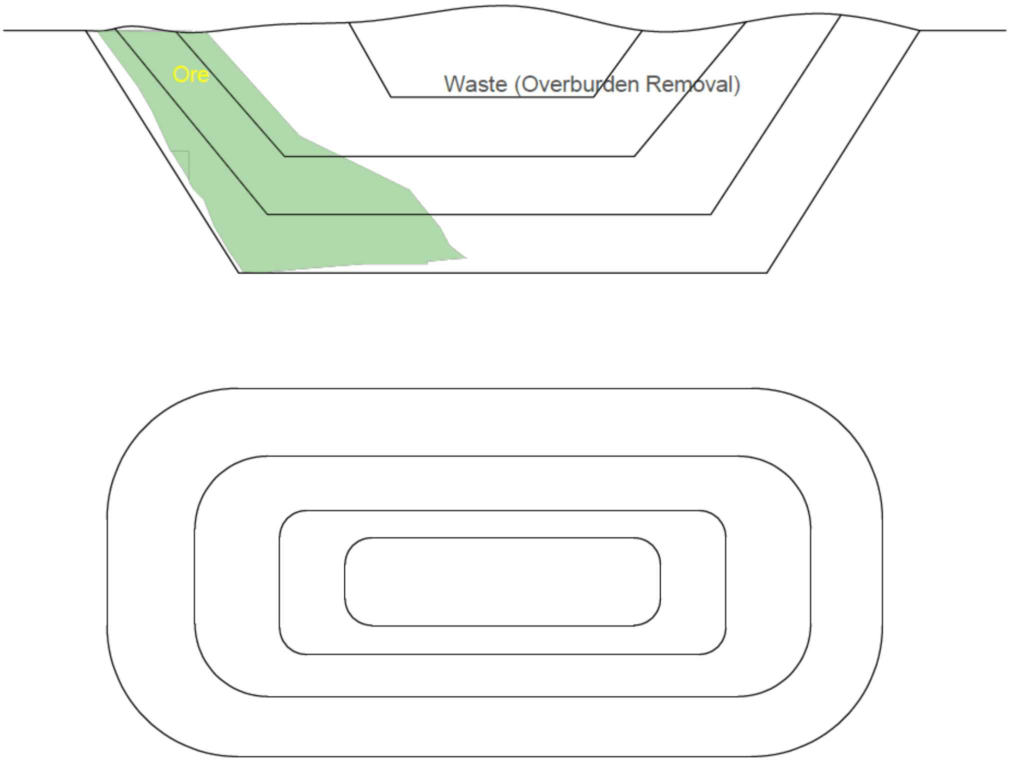

Figure 8: *schematic view of cross-section and plan of option B*

$$C_a = C_d(V_p + P_k) + \sum_{i=1}^{n} C_t l_i (V_{pi} + P_{Ki}); \ldots .3$$

n = is the number of horizons inside a quarry space,

V_{pi}, P_{Ki} = are overburden rock and mineral volumes on the horizon number "i", m3,

l_i = f(Hi) = is the distance of transportation of rock mass from the i – horizons to the surface, km,

Hi = is i – horizon bedding depth, m,

Cd = cost of all processes except transportation as a constant value,

Ct = rock mass transportation costs.

Characteristics of materials that are covered by the central Ayanak copper deposit and bearing copper minerals. Detailed information on their geological age, formation, stratigraphic members, thicknesses, lithological characteristics, and dominant sulphide minerals is shown in Figure 9 (Waizy et al., 2020).

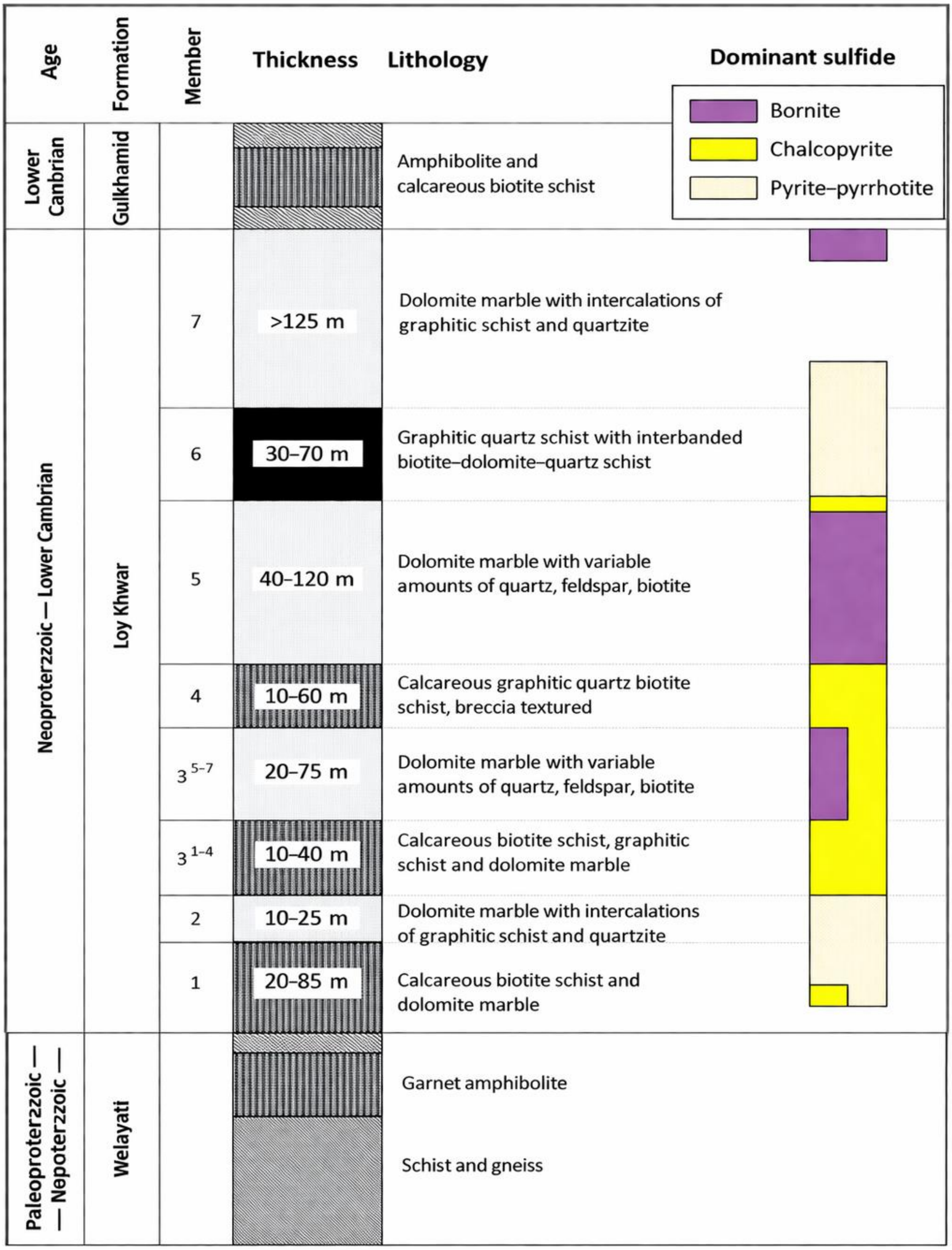

Figure 9: *Rock characteristic of Ayanak copper deposit (Waizy et al., 2020).*

Orientation Evaluation for Orientation from the Eastern Side to the Center (Option A)

According to Figure 9, the table indicates that the dominant minerals present in the Aynak area include dolomitic marble, graphitic schist, quartzite, feldspar, biotite, garnet, amphibolite, and several sulfide minerals such as bornite, chalcopyrite, and pyrite Based on the Mohs hardness scale (Maričić et al., 2018), these minerals range in hardness from 2 to 7.5, reflecting both soft and hard mineral assemblages within the deposit. Specifically, dolomitic marble has a hardness of 3.5–4 (Dietrich), quartzite is 7and feldspar is 6 (Maričić et al., 2018). shorter axis, from side to center, along the longer and shorter axes; central and elliptical orientations available. According to the schematic shown in Figure 7, the mineral deposit extends predominantly along the west-to-center axis, which represents the ore body's longer structural direction. The geometry of the deposit supports a progressive excavation approach from the western flank toward the central zone, ensuring maximum ore recovery (Xiang et al., 2025) while maintaining overall pit stability, as determined by the safety formula. Dump trucks are primarily used to haul both overburden and ore from the active benches to dumping or processing sites (Shamsi et al., 2022), while cars and auxiliary vehicles facilitate the movement of personnel and smaller equipment within the mine area, and uncrewed vehicles (Zhang et al., 2020). This integrated transportation system improves operational efficiency and ensures a continuous flow of material throughout the mining process. Selecting orientation for mining is the core concept for mining enterprises in the first stage of development (Zhou et al., 2023). Moreover, some units are really available for min, whereas extrac involves a lot, which is available (Altinpinar et al., 2021). According to Figure 7, a total of 4 overmethod urden removal methods have been designed for the extraction process. The first overburden removal serves a dual purpose: it supports mine development and overburden removal, and it supports the initial stages of ore extraction. As mining progresses, subsequent benches are developed downward in steps, following the geometry of the ore body defined through geological studies and mapping. This bench configuration allows for stable slope conditions and systematic ore extraction. The mining operation continues progressively through each bench until the entire deposit has been extracted. The illustration is shown in Figure 10.

Figure 10: *Schematic view of the removal of overburden*

The first stage serves as a preparatory phase for deeper mining activities, establishing the access ramps, benches, and drainage systems required for subsequent operations. During this stage, the removal of overburden is closely coordinated with the initial exposure of the ore zone to ensure operational continuity and minimize non-productive time.

Orientation Evaluation for Orientation from Center to Eastern and Western Side (Option B)

Based on the schematic representation in Figure 8, the mining orientation during the development stage at the Aynak copper deposit follows an open-pit configuration that progresses from the central zone toward both flanks of the deposit. Once the initial overburden is cleared, the ore body becomes exposed, allowing for subsequent extraction activities. Following exposure, the mining operations advance simultaneously on both sides of the ore body, proceeding from the lower levels upward. This staged approach enables efficient ore recovery while maintaining pit stability. The excavated material, including both ore and waste, is systematically transported toward the two pit boundaries, where it is either processed or stockpiled, depending on its economic value. This orientation strategy optimizes pit development by facilitating balanced material handling, progressive slope formation, and safe access to successive benches, ensuring effective resource extraction during the early phases of open-pit development at Aynak (see Figure 11 for more details).

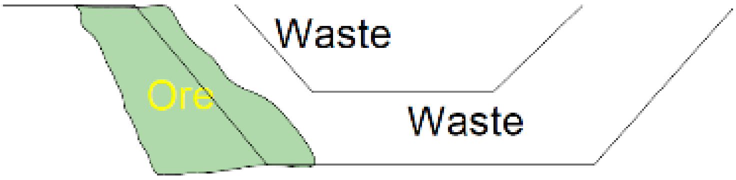

Figure 11*: Schematic of pit extraction for option B.*

According to the schematic Figures 8 and, during the first stage of pit development, the stripping ratio is not applicable, as no ore extraction occurs at this stage. The entire material removed consists solely of overburden and waste rock, which must be cleared to expose the underlying mineralized zone. This phase represents the initial pre-stripping operation, in which the objective is to establish access to the orebody by systematically removing barren material. Such activities include pit shaping, construction of haul roads, and bench formation, all of which contribute to preparing the mine for productive extraction in subsequent stages.

All these geotechnical parameters will be systematically evaluated based on the schematic plan and graphical representations illustrated in Figure 7 and of the Aynak copper deposit study. These figures provide the spatial and structural framework required for assessing various design alternatives. Following the evaluation, the optimal orientation and configuration for the mine will be selected to achieve the best balance between safety, economic efficiency, and operational practicality.

Operational Efficiency

One of the most significant considerations in open-pit mining is optimizing haulage distance, as the transportation of ore and waste material accounts for a large share of operating costs and energy consumption (Čelebić et al., 2024). Also, environmentally friendly for sustainable extraction (Bao et al., 2023). The Western-to-center (Option A) orientation scenario demonstrates reduced transportation distances, as ore is more easily accessible with less initial excavation. This reduction in haulage requirements not only enhances efficiency but also lowers overall energy demand, aligning with principles of cost-effective mine design. By contrast, in the option B scenario, the centric expansion necessitates longer haulage routes and more extensive excavation, resulting in higher operational expenditure and greater fuel consumption. According to the total variable haul cost (energy/emissions) across the pit. The transportation system is clearly shown in Figure 12 below.

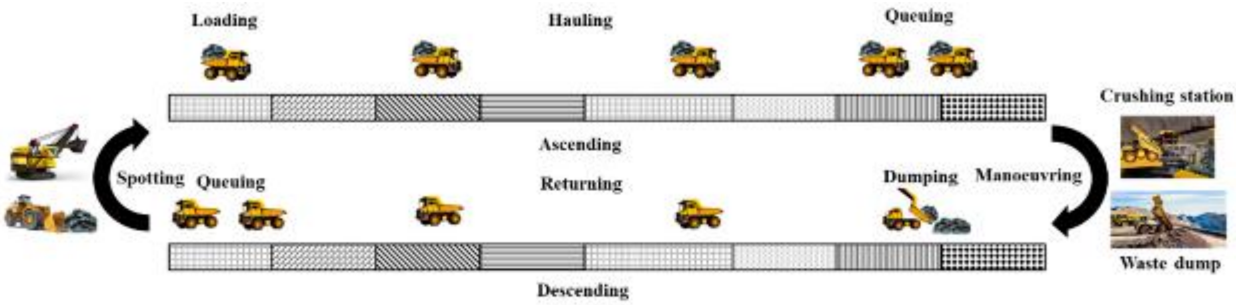

Figure 12: *Haulage system for open pit mine extraction (Haiming Bao et al., 2023).*

Waste Management and Land Disturbance

Mining waste is generated in every mining operation; it depends on the extraction method and the location where the waste is stored (Reno, 2015). The spatial arrangement of waste dumping areas also differs substantially between the two scenarios. The centric approach creates larger and more dispersed dumping zones, thereby expanding the total footprint of disturbed land and complicating the long-term rehabilitation process. Conversely, the west-to-center orientation facilitates the use of mined-out areas for backfilling and waste storage. This not only minimizes the external land area allocated for waste disposal but also improves the overall manageability of mine waste. Such practices are consistent with sustainable mining principles, which emphasize reducing surface disturbance and integrating waste management into the mining cycle (Reno, 2015).

Environmental Implications

Environmental sustainability is an essential concept for future humanity and the integrity of the resources and ecosystems on which we depend (Yang et al., 2026). Environmental degradation represents a critical dimension of mining sustainability. The results indicate that the orientation from western side to Center (Option A) scenario is environmentally favorable due to several factors: (i) shorter haulage distances reduce greenhouse gas emissions and noise pollution from transport vehicles, Total variable haul cost (energy/emissions) across the pit, (ii) the lower volume of overburden limits soil and landscape disturbance, and (iii) a smaller dumping footprint decreases the risk of ecological fragmentation and long-term land degradation. In contrast, the orientation from the center to the western and eastern sides (option B) scenario amplifies these impacts due to greater material movement and land-use requirements. Therefore, the west-to-center strategy not only enhances operational feasibility but also aligns with broader environmental management goals aimed at minimizing the ecological footprint of mining operations. Strategic and Long-Term Implications Strategic extraction plays a crucial role in ensuring that mining practices are both environmentally friendly and sustainable (Firoozi et al., 2024).

Owing to its geological characteristics and proximity to the surface, the Aynak deposit is particularly suitable for open-pit mining, a method widely recognized for its efficiency in extracting near-surface mineral resources. Two alternative development scenarios were evaluated: (1) An unidirectional orientation expanding from the western side towards the center along the deposit's axis. (2) A centric progression expanding outward from the deposit's center towards both the eastern and western margins. The comparative assessment was based on key operational and environmental parameters, including haulage distance, waste-dumping requirements, overburden volume, and associated environmental impacts. The findings suggest that the first scenario, characterized by a west-to-center orientation, offers distinct operational and environmental advantages, thereby providing a more sustainable extraction strategy. From a long-term planning perspective, the west-to-center scenario also offers advantages in terms of technical simplicity and scalability. The linear progression of pit expansion provides a more predictable excavation sequence, reduces geotechnical risks associated with irregular pit geometry, and allows for incremental development that is easier to monitor and adjust. These attributes improve both the safety and sustainability of the operation, contributing to a more robust mining strategy. Furthermore, integrating environmental and operational considerations into this orientation underscores the potential to harmonize resource extraction with sustainable development objectives; for more information, see Figure 13.

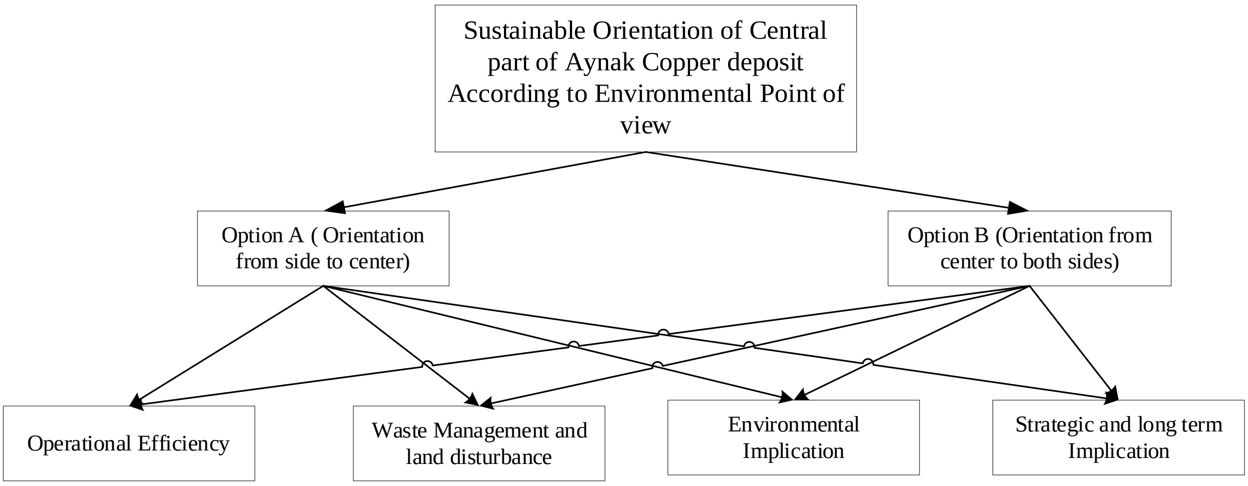

Figure 13: *Elements that affect the Sustainable orientation of mining.*

The Analytic Hierarchy Process (AHP) is a systematic decision-making method that decomposes a complex problem into a hierarchical structure, compares elements through pairwise comparisons, and synthesizes these judgments to determine the relative priorities of criteria and alternatives (Tavana et al., 2023).

Table 5: *Analytic Hierarchy Process (AHP) table for decision making for both options*

Factors based on Environmental consideration	Weight	Option A	Option B
Operational efficiency	0.2	0.8	0.6
Waste management and land disturbance	0.3	0.7	0.5
Environmental Implication	0.3	0.7	0.3
Strategic and long-term implications	0.2	0.6	0.5
Final score	1	0.70	0.46

Two orientation methods were selected for the Aynak copper deposit, and each option was assigned a score. These options were evaluated using the Analytical Hierarchy Process (AHP). Based on the results, the option with the highest score was identified as the most suitable orientation in terms of environmental considerations, operational efficiency, waste management, land disturbance, and long-term strategic implications. The preferred option is the orientation from the western side toward the center (Option A), which achieved the highest score (0.70). Therefore, this option is considered the optimal solution, as determined through the matrix evaluation in Table 5 below.

Conclusion

In conclusion, copper deposits play a crucial role in the industrial development of modern economies due to their extensive use in electrical, construction, and technological sectors. Afghanistan is endowed with vast copper reserves, among which the Aynak copper deposit in Logar Province is among the most significant. In this research, two alternative orientation options were analyzed for the Aynak deposit. Option A proposes an orientation from the western side toward the central part, whereas Option B suggests a central orientation that extends toward both the western and eastern sides. A comprehensive geological study was conducted to evaluate the ore body characteristics, overburden composition, and geotechnical properties of the Aynak deposit. In addition, a Digital Elevation Model (DEM) of the area was generated and analyzed in QGIS. The DEM analysis provided a detailed understanding of the topographic relief, slope gradients, and overall morphology of the deposit and its surroundings. The integration of both field data and secondary sources enabled a robust evaluation of the two orientation options. Based on the combined geological, environmental, and operational analyses, Option A, the orientation from the west side toward the central zone, was determined to be the most favorable configuration for the Aynak copper deposit. From an environmental standpoint, several factors contributed to the preference for Option A. The first factor is topographical suitability; the second is reduced environmental impact; the third is simplified land management and stability control; and the fourth is efficient material handling and waste management. Consequently, the project benefits from both cost efficiency and environmental protection.

Reference

Afghanistan Geological Survey, & British Geological Survey. (2005). *Aynak information package: Part I, introduction.* Afghanistan Geological Survey.

Ali-Elbeblawi, M. M., Abdelhak Elsaghier, H. A., Mohamed Amin, M. T., & Elrawy Abdellah, W. R. (2022). Surface Mining Technology. *Springer Singapore*. https://doi.org/10.1007/978-981-16-3568-7

Altinpinar, M., & Ortiz, J. M. (2021). A quick guide to developing a mine plan. Predictive Geometallurgy and Geostatistics Lab, *Queen's University*.

Baek, J., & Choi, Y. (2017). A New Method for Haul Road Design in Open-Pit Mines to Support Efficient Truck Haulage Operations. *Applied Sciences, 7(7)*, 747. https://doi.org/10.3390/app7070747

Bao, H., Knights, P., Kizil, M., & Nehring, M. (2023). Electrification Alternatives for Open Pit Mine Haulage. *Mining, 3(1)*, 1–25. https://doi.org/10.3390/mining3010001

Benham, A. J., Coats, J. S., & Kovac, P. (2024). Aynak: A world-class sediment-hosted copper deposit, Afghanistan. British Geological Survey.

Bowell, R. J., Williams, C. R., Merry, E. J., Carpenter, A., Bertrando, K., & Parshley, J. V. (2023). Mitigation of Mining Effects on the Environment. *SEG Discovery*, (135), 27–43. https://doi.org/10.5382/Geo-and-Mining-21

Cao, B., Wang, J., Guo, X., Li, W., & Liu, G. (2023). Research on boundary optimization of adjacent mining areas in open pit coal mine based on calculation of sectional stripping ratio. *Scientific Reports, 13(1),* 21286. https://doi.org/10.1038/s41598-023-48708-y

Čelebić, M., Bajić, D., Bajić, S., Banković, M., Torbica, D., Milošević, A., & Stevanović, D. (2024). Development of an Integrated Model for Open-Pit-Mine Discontinuous Haulage System Optimization. *Sustainability, 16(8),* 3156. https://doi.org/10.3390/su16083156

Dietrich, R.V.. "dolomite". *Encyclopedia Britannica*, 8 Jan. 2024, https://www.britannica.com/science/dolomite-minera

Firoozi, A. A., Tshambane, M., Firoozi, A. A., & Sheikh, S. M. (2024). Strategic load management: Enhancing eco-efficiency in mining operations through automated technologies. *Results in Engineering*, *24*, 102890. https://doi.org/10.1016/j.rineng.2024.102890

Gunawardhana, S., Dushyantha, N., Nipunika, G., Rathnayake, S., Kuruppu, G. N., Weerakoon, P., & Cooray, T. (2025). Sustainable pathways for rural sand mining: Integrating socioeconomic resilience, financial viability and environmental stewardship in Badulu Oya, Sri Lanka. *The Extractive Industries and Society, 24*, 101744. https://doi.org/10.1016/j.exis.2025.101744

Hartman, H. L. (2002). Introductory mining engineering. John Wiley & Sons.

Jiskani, I. M. (2017). *Surface Mine Design.* https://doi.org/10.13140/RG.2.2.12675.55843

Little, J. C., Hester, E. T., & Carey, C. C. (2016). Assessing and Enhancing Environmental Sustainability: A Conceptual Review. *Environmental Science & Technology, 50(13),* 6830–6845. https://doi.org/10.1021/acs.est.6b00298

Maričić, A., Starčević, K., & Barudžija, U. (2018). Physical and mechanical properties of dolomites related to sedimentary and diagenetic features – Case study of the Upper Triassic dolomites from the Medvednica and Samobor Mts., NW Croatia. *The Mining-Geology-Petroleum Engineering Bulletin.*

Mensah, A. K., Mahiri, I. O., Owusu, O., Mireku, O. D., Wireko, I., & Kissi, E. A. (2015). Environmental impacts of mining: A study of mining communities in Ghana. *Applied Ecology and Environmental Sciences, 3(3),* 81–94. https://doi.org/10.12691/aees-3-3-3

Noorhan, W. (2017). Feasibility study of Aynak copper deposit: Logistics, infrastructure, processing and auxiliary operations

OceanaGold. (2020). Mining extraction. https://oceanagoldmacraes.co.nz/projects/mining/mining-process/open-pit-mining

Oggeri, C., Fenoglio, T. M., Godio, A., & Vinai, R. (2019). Overburden management in open pits: Options and limits in large limestone quarries. *International Journal of Mining Science and Technology, 29(2),* 217–228. https://doi.org/10.1016/j.ijmst.2018.06.011

OpenTopography. (2021). *Copernicus GLO-90 Digital Surface Model*. OpenTopography. https://doi.org/10.5069/G9028PQB

Poblete, C. J., González, M. A., Romero, J. A., & Fuentes, D. L. (2016). Impact of the starting point and of the direction of open pit exploitation on the mining plan. *Center of Excellence of the Americas*, Dassault Systèmes, Chil

Rahimdel, M. J., & Mohammadpour, R. (2025). Enhancing mineral transportation systems in underground mines: A framework for capacity analysis. *Heliyon, 11(4),* e42708. https://doi.org/10.1016/j.heliyon.2025.e42708

Rakhmangulov, A., Burmistrov, K., & Osintsev, N. (2021). Sustainable Open Pit Mining and Technical Systems: Concept, Principles, and Indicators. *Sustainability, 13(3),* 1101. https://doi.org/10.3390/su13031101

Rakhmangulov, A., Burmistrov, K., & Osintsev, N. (2022). Selection of Open-Pit Mining and Technical System's Sustainable Development Strategies Based on MCDM. *Sustainability, 14(13),* 8003. https://doi.org/10.3390/su14138003

Reno, J. (2015). Waste and Waste Management. *Annual Review of Anthropology, 44(1),* 557–572. https://doi.org/10.1146/annurev-anthro-102214-014146

Reyes, C., Castillo, E., Orellana, L. F., & Del Real, I. (2025). Mining in the lithium triangle: A multifaceted approach towards resource development in the face of climate, governance, and socio-environmental challenges. *The Extractive Industries and Society, 24*, 101761. https://doi.org/10.1016/j.exis.2025.101761

Shafai, H., Asifi, A., Akbar, Q. (2021). Mineral resources in Afghanistan. Ministry of Mines and Petroleum, Islamic Republic of Afghanistan.

Shafayi, S. H., & Torab, F. (2022). Ore Deposit Boundary Modification in Afghanistan Aynak Central Copper Deposit using Sequential Indicator Simulation and Indicator Kriging. *Journal of Mining and Environment,* 13(2). https://doi.org/10.22044/jme.2022.11557.2142

Shamsi, M., Pourrahimian, Y., & Rahmanpour, M. (2022). Optimisation of open-pit mine production scheduling considering optimum transportation system between truck haulage and semi-mobile in-pit crushing and conveying. *International Journal of Mining, Reclamation and Environment, 36(2),* 142–158. https://doi.org/10.1080/17480930.2021.1996983

Shustov, O. O., Pavlychenko, A. V., Bielov, O. P., Adamchuk, A. A., & Borysovska, O. O. (2020). Calculation of the overburden ratio by the method of financial and mathematical averaged costs. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, (5),* 30–36. https://doi.org/10.33271/nvngu/2021-5/030

Tavana, M., Soltanifar, M., & Santos-Arteaga, F. J. (2023). Analytical hierarchy process: Revolution and evolution. *Annals of Operations Research, 326(2),* 879–907. https://doi.org/10.1007/s10479-021-04432-2

Taylor, C. D., Peters, S. G., Goldfarb, R. J., & others. (2011). Summary of the Aynak copper, cobalt, and chromium area of interest, Afghanistan. *U.S. Geological Survey Open-File Report.*

U.S. Geological Survey. (2016). EarthWord—Ore. https://www.usgs.gov/communications-and-publishing/news/earthword-ore

Waizy, H., Moles, N. R., Smith, M. P., & Boyce, A. J. (2021). Formation of the giant Aynak copper deposit, Afghanistan: Evidence from mineralogy, lithogeochemistry and sulphur isotopes. *International Geology Review, 63(17),* 2104–2128. https://doi.org/10.1080/00206814.2020.1824129

Xiang, J., Chen, J., Zhang, A., Zhao, X., Zhuo, S., & Yang, S. (2025). Multi-Objective Ore Blending Optimization for Polymetallic Open-Pit Mines Based on Improved Matter-Element Extension Model and NSGA-II. *Mathematics, 13(11),* 1843. https://doi.org/10.3390/math13111843

Yang, X., Kang, X., He, M., Wang, Y., Zhang, J., Shi, Z., & Chen, Y. (2026). Development characteristics and prediction methods of the "three zones" in overlying strata under the 110 mining method. *Rock Mechanics Bulletin, 5(1),* 100234. https://doi.org/10.1016/j.rockmb.2025.100234

Zhang, S., Lu, C., Jiang, S., Shan, L., & Xiong, N. N. (2020). An Unmanned Intelligent Transportation Scheduling System for Open-Pit Mine Vehicles Based on 5G and Big Data. *IEEE Access, 8,* 135524–135539. https://doi.org/10.1109/ACCESS.2020.3011109

Zhou, B., & Liu, T. (2023). The impact of economic performance on the environmental protection orientation of mining enterprises: A case study of the Yangtze River Economic Belt in China. *Resources Policy, 86,* 104169. https://doi.org/10.1016/j.resourpol.2023.104169