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# Determination of an Optimum Interface between Open-Pit and Underground Mining Activities in Mazinu Coal Mine of Tabas Power Plant

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***Abstract***

Due to the gradual deepening of the Mazinu coal seams from the ground surface, both the open-pit (OP) and underground (UG) mining methods can be applied for extracting them. Thus, it is a necessity to determine the interface of these mining methods optimally. The present paper aims to determine this interface by generating different scenarios using the OP phases and their relative underground stopes, and comparing them with each other. In this regard, an economic block model is created based on the calorific value of the coal portions involved by each block along with the required economic and technical parameters. Then using the Lerchs-Grossman algorithm, the OP phases are created. Proportional to each phase, the production scheduling of underground stopes is executed. Finally, in order to opt the best scenario, the net present value of the whole project (OP & UG) achieved from different scenarios are compared with each other. The results obtained indicate that the optimum interface of the OP and UG mining activities correspond to the ultimate OP limit with a maximum depth of 200 m from the ground surface.

## 1. Introduction

The amount of calorific value that is required for generating 1 kWh of electrical power has always been reducing over the time. This is because of applying the technological modifications in the construction of boilers and development of new coal concentering techniques [1]. The modern technologies applied to the boilers of the Mazinu power plant have provided the possibility of consuming coals with an ash content up to 50%. This enables the mine planners to extract about 3 Mt/annum mixture of the superior and inferior grades of coal reserves in cast of some coal bands with a 6.5 m thickness. This production rate equals to the current production capacity of Iran coal mines, which are mostly extracted by a type of underground (UG) mining method. The existing infrastructures of the open-pit (OP) mining method along with the geometry of the Mazinu coal seams imply that surface mining is the most suitable method to meet the planned feeding rate of the plant. However, due to the gradual deepening of the Mazinu coal seams from the ground surface, the deep portions of coal seams are expected to be extracted by the UG mining method. The possibility of applying both the OP and UG mining methods to the Mazinu coal mine conveys the necessity of determining the best location where these mining methods interface with each other. In order to have a reasonable solution in this regard, the effects of the technical principles of each mining method should be considered in the evaluations since the different mining principles will result in different production capacities, unequal mining costs, and various qualities of the extracted materials. These differences are eventually reflected in the cash flow of each mining method. It is commonly expected that in the case of OP mining of coal seams, compared to the

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UG mining method, the mine production rate and the quality of the extracted coal will increase and decrease, respectively. For an example, by changing the coal mining method in India from UG to OP, in spite of earning more products, the quality of the extracted material decreased due to the lack of control on mining the hanging and foot walls [2]. The emerging tendency toward OP mining of coal seams may be due to the technological improvements like what has happened in the Mazinu Power plant. However, the other technologies that have led to the manufacture of high capacity dump trucks and high steep belt conveyers, producing the softwares and tools that are used for slope stability of OP walls might have been impressive in this regard. Anyway, the OP coal mines, like other OP mines, will continue to a specific depth, and the rest of coal seams will be extracted by the UG mining method. Thus, the best interface between the OP and UG mining methods in such mines should be determined by balancing the pros and cons of these methods in contrast to each other. For example, in Table 1, the OP and UG mining methods are compared in regard with the total mining costs and the quality of extracted coal. These criteria are reflected into one economic specific index, e.g. net present value (NPV).

**Table 1. Comparing the OP and UG methods in regard with the main criteria.**

| Criterion | | General expected result | | |
|---|---|---|---|---|
| Total extraction costs per ton of coal | In shallow depths before transition zone | UG | > | OP |
| | Within transition zone | UG | ≈ | OP |
| | In high depths after transition zone | UG | < | OP |
| Coal quality (calorific value) | | UG | ≥ | OP |

## 2. Literature review

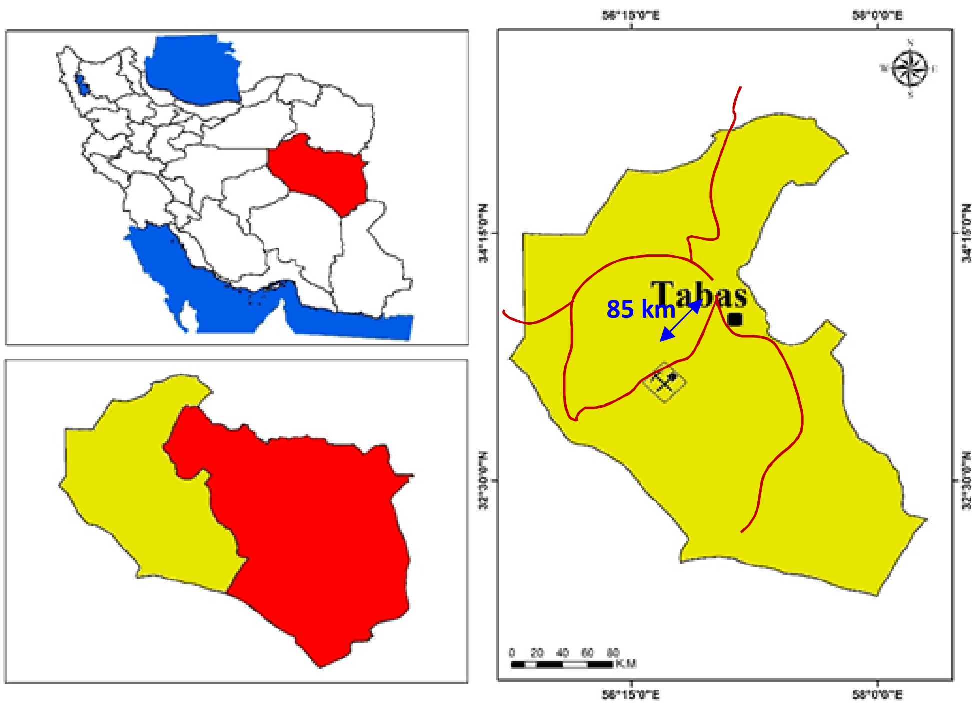
The allowable stripping ratio (ALSR), as the early solution method, has been developed in order to find a depth at which the OP and UG mining costs are equal. This approach can be traced in Soderberg [3] and Popover [4]. With the prevalence of making economic decisions based on the projects' NPV, Nilsson has tried to determine the transition depth based on NPV of the whole deposit [5]. Taking one step backward, Chen has tried to combine the ALSR method with the mathematical calculations of ore and waste volumes [6, 7]. Visser and Ding have tried to apply the Nilsson's method in a try-and-error process to find the optimum transition depth [8]. Over the time and with prevailing the operational research techniques in mining industry, Bakhtavar *et al.* have tried to determine the optimum transition depth through the long-term production scheduling of the OP and UG portions [9]. Their model was a 2D integer programming one and could be applied in vertical sections. Newman *et al.* (2013) have sub-divided a whole deposit into some horizontal planes in order to be scheduled for finding the transition depth [10]. However, the problem was still being solved in a 2D form and thus the optimum solution could not be achieved. Dagdelen and Traore have tried to find the optimum transition depth by selecting some scenarios from the OP phases [11]. They used the Lerchs and Grossman algorithm [12] in order to create these phases. Although the transition depth is in the shape of these pre-defined scenarios, the transition depth can be determined in a 3D shape. In order to determine the transition interface between the OP and UG mining methods in a coal mine, Ordin and Vasil'ev have calculated NPV of these methods separately at first, and then using a dynamic programming, they searched for the maximum NPV of their combinations [13]. The low solution speed of dynamic programming method and inexact form of their combining method are the two deficiencies of their approach. In addition, some recent studies have tried to solve the transition problem through the production scheduling of the entire orebody [14-18]. Since these studies have focused on specific cases, Soltani Khaboushan and Osanloo have classified a variety of transition problems and optimization models comprehensively [19].

In spite of the previous valuable studies conducted over the transition problems, there are a limited number of research works that have focused on determining the transition depth between the OP and UG mining methods in coal mines. Hence, in the present study, we tried to apply the existing approaches in coal regions and specifically in the Mazinu coal bearing area. During this work, different characteristics of each method such as different production capacities, losses, and dilution factors were considered.

## 3. Materials and methodology

### 3.1. Mazinu coal mine

The Mazinu coal mine is located 85 Km SW of Tabas in the Southern Khorasan Province, Iran (Figure 1). According to the plans, 650 MW of electrical power is to be generated from 75 Mt of minable thermal coal reserves laid just adjacent to the plant. The mine life is estimated to be 25 years, and 3 Mt/Annum of coal is to be extracted for feeding the plant. The minimum and maximum thicknesses of minable coal seams are 0.5 and 1.8 m, respectively. It has been planned to extract the coal seams in cast of coal bands including the coal and interbedded waste layers with a thickness up to 6.5 m. From more than 20 number of explored coal seams, 9 seams are to be extracted. These seams dip gradually (20-30 degrees) toward SE.




(a) (b)

**Figure 1. Location of Mazinu coal mine in Iran: (a) Location of Tabas in the Khorasan razavi Province and Iran; (b) Location of the Mazinu coal mine in Tabas.**

### 3.2. Methodology

Calculation of the calorific value of minable coals that will be extracted by each mining method is necessary before determining the best interface between them. Thus, before solving the problem, two economic block models should be created based on a unique geological model. In the present work, the equivalent monetary value of electrical power that could be generated from each sub-block was considered as the basis of creating the economic block models. The technical and economic parameters of each mining method were considered through the creation process of economic models. Calculation of economic value of an independent sub-block will be described in a separate section.

Whenever the economic models are provided as the input data to the optimization process, the same approach applied by Dagdelen and Traore [11] is followed to solve the problem. Thus, some OP phases are created using the Lerchs and Grossman approaches [12] as the scenarios. It is assumed that the remaining portions of coal seams behind each OP phase will be extracted by the UG method. NPV of the OP and UG portions of each scenario are calculated separately. The OP and UG results are accumulated for each scenario. Finally, the scenario with the maximum value is selected as the best option. Figure 2 briefly shows the applied solution process.

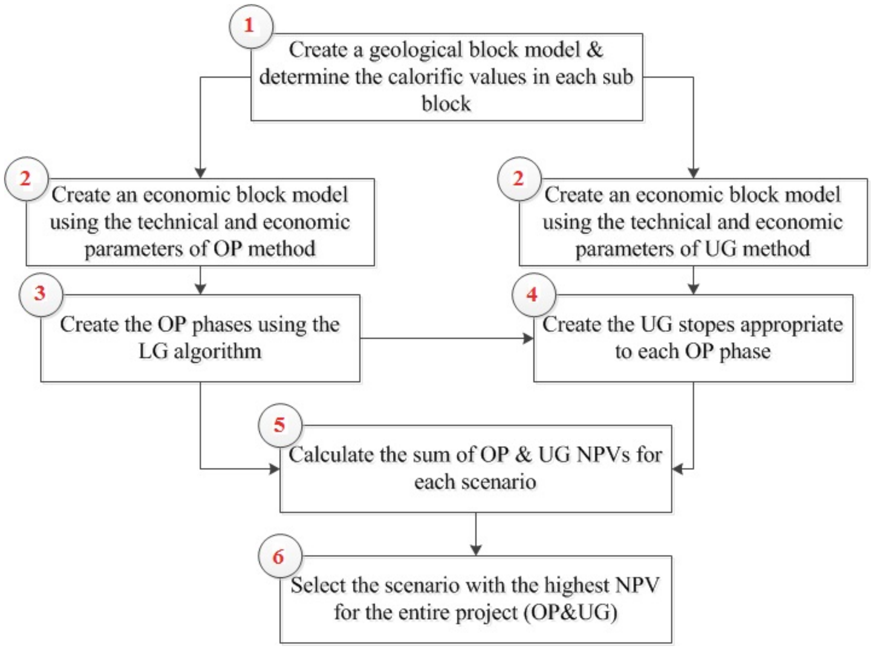



**Figure 2. Solution process of the transition problem.**

While creating different OP-UG scenarios, the following tips were considered in this work:

- In order to control the ground subsidence and prevent the slope failures in the OP portion, the coal seams were first extracted by the OP method, and the remaining portions would be extracted by the UG method. Thus, the economic values of the UG blocks would be more discounted.
- Some portions of coal seams would remain unmined between the OP and UG portions. The existence of these pillars are due to the requirements of the UG method. Hence, the refusal of their companionship to the mine economy pertain to the UG portion. These pillars reduce the competitive capability of the UG portion against the OP portion. However, the recovery of some parts of these pillars may improve this competitive capability to some extent.
- In order to provide the safety and control of the ground subsidence, an UG stope should be mined out fully whenever its extraction is started. Thus, the sporadic mining of sub-blocks from various mining stopes is not suggested. In order to impose this matter to the UG production scheduling, the economic values of sub-blocks were aggregated in cast of the UG stopes. Thus, the UG scheduling program would be executed on the stopes.
- The lateral distance at the bottom of two adjacent phases was equal to the width of the UG stopes. This was done to justify the commissioning costs of an UG stope proportionate to the amount of coal that was extractable from its space.
- Due to the high extent of coal seams (up to 7 Km) in the Mazinu mine, the largest sector of mine was used for the evaluations.

### 3.3. Calculation of block economic values (BEVs)

Calculation of the economic values of the OP and UG sub-blocks differs from each other because in the OP operation, in addition to coal seams, the waste rocks should be extracted as well. However, in the UG mining method, just the coal seams are planned to be extracted. In case of extracting the block shown in Figure 3 by the UG method, just the mining costs of coal portion (seam B) are considered for the BEV calculations. However, in case of extracting the same block by the OP method, the mining costs of the upper and lower waste rocks (A and C) should be imposed to the BEV calculations. For the blocks that involve the bottommost coal seam, the mining costs of the B and C portions are considered because the OP operation does not extend beneath the footwall of the bottommost seam. Equations (1) and (2) show how the OP and UG BEVs are calculated in the Mazinu coal mine based on the amount of electricity that can be generated from the coal portions of each sub-block.

$$\begin{aligned} BEV^{OP} &= O \times R_M^{OP} \times (1-L^{OP}) \times (Q_i / 860 \times 1000) \times R_{PP} \times P_P \\ &- (O+W) \times (C_M^{OP} + C_Z^{OP}) - O \times R_M^{OP} \times (1+d^{OP}) \times C_H \\ &- W \times C_D - O \times R_M^{OP} \times (1+d^{OP}) \times C_{PP} \end{aligned} \quad (1)$$

$$\begin{aligned} BEV^{UG} &= O\times R_M^{UG}\times(1-L^{UG})\times(Q_i/860\times1000)\times R_{PP}\times P_P \\ &-O\times(C_M^{UG}+C_Z^{UG})-O\times R_M^{UG}\times(1+d^{UG})\times C_H \\ &-O\times R_M^{UG}\times(1+d^{UG})\times C_{PP} \end{aligned} \quad (2)$$

For the BEV calculations, it is important to know the relationships between the calorific value and the impressive factors like the ash and sulfur contents. In the Mazinu coal mine, the range of these factors is very different from each other. Thus, the raw data was normalized at first. Then, in order to concurrently determine the type of correlations, these variables were drawn in a 3D space and a plane was fitted on them (Figure 4). The results obtained indicate that the calorific values have an inverse and strong correlation with the ash content. The sulfur content has a dual and limited impact on the calorific values such that in low ash-bearing coals, the sulfur increment decreases the calorific values to some extent. However, in high ash-bearing coals, due to the sulfur increment, the calorific values increase slightly. In other words, in the coal specimens, when the ash content decreases, the sulfur will affect the calorific values more.

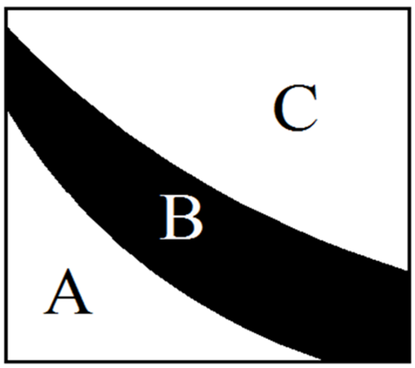



**Figure 3. A sub-block that includes a coal seam.**

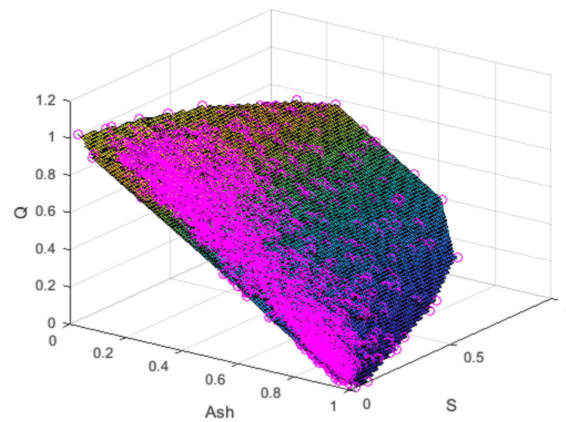



**Figure 4. Relationship between coal calorific value and ash and sulfur contents in Mazinu.**

The loss and dilution depend on the type of ore and waste intertwinement, mining method, and scale of mining operations. These parameters were calculated based on the real experiences of the adjacent OP coal mines near the Mazinu mine. In the OP mining, considering that 10 Cm of the upper waste rocks were extracted with coal seams and 5 Cm of each coal seam remained unmined at its bottommost, the loss and dilution values were considered to be 3.8% and 2%, respectively. In the UG operation, it was supposed that the dilution would be about zero. However, the ore losses were assumed to be equal to that of the OP operation. The recovery of coal seams in UG mine was considered to be 100% for the portions that were located within the working stopes. It was assumed that the coal portions that remained unmined in pillars would not be recovered at all. This way, the total recovery of coal seams in the UG operation would be about 70%. In the OP operation, the partial and overall recoveries will be 100%. This means that all portions of coal seams are extracted in the Op operation apart from their destinations. Table 2 shows the technical and economic parameters that have been used in the calculations of BEVs in the Mazinu coal mine.

**Table 2. The OP and UG design parameters.**

| Parameter | Value | Unit |
|---|---|---|
| OP production rate | 3 | Mt/year |
| UG production rate | 0.5 | Mt/year |
| OP bench height | 10 | m |
| Op wall slope | 20-42 | Degrees |
| UG stopes size | 100 × 130 | Square meters |
| OP overall recovery | 100 | Percent |
| UG overall recovery | 70 | Percent |
| Discount rate | 15 | Percent |
| OP dilution | 3.8 | Percent |
| OP & UG losses | 2 | Percent |
| power price | 614.7 | Rilas/Kwh |
| OP mining cost | 50000 | Rials/ton |
| UG mining costs | 800000 | Rilas/ton |
| Haulage cost | 9000 | Rilas/ton.Km |
| Power plant costs | 140000 | Rilas/ton |

### 3.4. Optimization model

Khaboushan and Osanloo have presented various OP-UG transition models [17]. The optimum transition model that is applied for the Mazinu coal mine is a type of long-term production scheduling models that are used for non-simultaneous mining operations and are solved with a scenario-based strategy. The objective function is written according to Equation (3) for maximizing NPV of the whole Mazinu project (OP & UG). Equations (4) and (5) are discount factors that are imposed to the OP and UG BEVs, respectively.

$$Max\left(\sum_{t}^{T}\sum_{b}^{B} BEV_b^{OP}\,\delta_t\,x_b^t + \sum_{p}^{P}\sum_{s}^{S} BEV_s^{UG}\,\delta_p\,y_s^p\right) \quad (3)$$

$$\delta_t = \frac{1}{(1+r^{OP})^t} \quad (4)$$

$$\delta_p = \frac{1}{(1+r^{UG})^p} \quad (5)$$

As it can be seen in Equation (3), the objective function consists of two parts for the OP and UG portions. This way, the OP blocks and UG stopes are scheduled separately. BEVs of the OP blocks are considered directly in the optimization process. In the UG portion, however, before commencing the optimization process, the economic values of stopes are calculated based on the blocks that are involved by them (Equation 6). The ash content of each UG stope is calculated according to Equation (7). In these equations, the index s is used to show the UG stopes. It is notable that the economic values of the OP and UG scheduling units are discounted with different discount rates.

$$BEV_s^{UG} = \sum BEV_b^{UG} \qquad \forall s \in S \,|\, b \in s \quad (6)$$

$$Ash_s^{UG} = \frac{\sum Ash_b^{UG} \times O_b^{UG}}{\sum O_b^{UG}} \quad \forall s \in S \,|\, b \in s \quad (7)$$

Each part of the objective function is optimized subject to its constraints. Although the written formats of the problem's constraint are alike, their upper and lower bounds and their matrixes, which are the input data to the solver, are different. In the following, the defined constraints for the present work are described.

*Reserve constraint:* Each scheduling unit, even in the OP portion or the UG portion, must be extracted once and only once. In other words, BEV of each unit contributes to the project cash flow once and only once. As in the OP portion all blocks within UPL must be mined, this constraint is in an equal format (Equation 8). However, in the UG portion, some parts of coal seams may remain unmined as the support pillars between the OP and UG portions. Thus, the reserve constraint for the UG portion is written in an inequality form (Equation 9).

$$\sum_{t=1}^{T} x_b^t = 1 \qquad \forall b \in B \quad (8)$$

$$\sum_{p=1}^{P} y_s^p \le 1 \qquad \forall s \in S \quad (9)$$

*Production constraint*: The production capacity of the OP and UG portions would be different in Mazinu. Generally, compared to the UG mining method, the higher production rate of the OP mining method is considered as a privilege. In Mazinu project, the production capacity of the OP portion has a better compatibility with the power plant consumption rate. In the UG portion, the wastes are extracted scarcely. In the OP portion, due to the necessity of meeting the plant feed, the waste removal constraint is released. In the present work, according to Equations 10 and 11, the capacity constraints of the OP and UG portions are set on the milling rate of the power plant for each portion.

$$Mill_{Min}^{OP} \le \sum_{b=1}^{B} O_b^{OP} \times x_b^t \le Mill_{Max}^{OP} \qquad \forall t \in T \quad (10)$$

$$Mill_{Min}^{UG} \le \sum_{s=1}^{S} O_s^{UG} \times y_s^p \le Mill_{Max}^{UG} \qquad \forall p \in P \quad (11)$$

*Sequencing constraints:* The sequences of the OP blocks and UG stopes are different from each other. The overall mining direction in an OP operation is downward. The mining is not restricted to a specific direction in the XY planes. In the UG operation, in addition to the main downward mining direction, the stopes should be extracted from the south-east toward the north-west in a retarding pattern. Thus, the similar constraints in shape are different in concept. The sequencing constraints are written as Equation 12 and 13.

$$n_b^t x_b^t - \sum_{u=1}^{n_b^t}\sum_{v=1}^{t} x_u^v \le 0 \qquad \forall b \in B \,\&\, t \in T \quad (12)$$

$$m_s^p y_s^p - \sum_{u=1}^{m_s^p}\sum_{v=1}^{p} y_u^v \le 0 \qquad \forall s \in S \,\&\, p \in P \quad (13)$$

Coal quality constraints: Based on the high correlation between the ash content and the calorific value that is shown in Figure 4, the quality constraints of the produced coal is defined on the ash content (Equations 14 and 15).

$$Ash_{Min}^{OP} \le \frac{\sum_{b}^{B} O_b^{OP} \times Ash_b^{OP} \times x_b^t}{\sum_{b}^{B} O_b^{OP} \times x_b^t} \le Ash_{Max}^{OP} \qquad \forall t \in T \qquad (14)$$

$$Ash_{Min}^{UG} \le \frac{\sum_{s}^{S} O_s^{UG} \times Ash_s^{UG} \times y_s^p}{\sum_{s}^{S} O_s^{UG} \times y_s^p} \le Ash_{Max}^{UG} \qquad \forall p \in P \qquad (15)$$

The upper and lower bounds of the coal quality constraints have been defined on the averages. Thus, the maximum and minimum ash content may trespass these values. As an example, the Mazinu power plant can accept feeds with a maximum ash content of 50%. The upper and lower limits of the production planning constraints are summarized in Table 3. It is also notable that the optimization model has been written in the form of an integer programming optimization model and the variables are binary ( $x_b^t$ & $y_s^p \in \{0,1\}$ ).

**Table 3. The upper and lower bounds of model's constraints.**

| Specific | Value | Unit |
|---|---|---|
| Maximum coal production from OP | 3 | Mt/period |
| Minimum coal production from OP | 2 | Mt/period |
| Maximum coal production from UG | 0.8 | Mt/period |
| Minimum coal production from UG | 0.2 | Mt/period |
| Block removal ratio for slope control in OP | 1:1 | - |
| Stope removal ratio for subsidence control in UG | 1:1 | - |
| Maximum ash content in OP coal product | 40 | % |
| Minimum ash content in OP coal product | 0 | % |
| Maximum ash content in UG coal product | 40 | % |
| Minimum ash content in UG coal product | 0 | % |

## 4. Results and Discussion

Determination of the best interface between the OP and UG mining operations in a scenario-based method has been commonly used during the past few years. The same method was applied in the present work for the Mazinu coal mine. In this regard, four OP phases were created based on the information presented in Table 2. Cross-sections of these scenarios that have been used for determination of the best interface between the OP and UG methods are depicted in Figure 5. Each one of the shells depicted in Figure 5 is a potential OP-UG interface. NPV of each shell is allocated to the OP portion of each scenario. The UG spaces that correspond to each OP shell are depicted in Figure 6. The production scheduling of these stopes has been planned in a retarding way and up to a down order. NPVs of the OP and UG portions and their summations are presented in Table 4. The maximum numerical result will determine the best physical solution (i.e. transition interface).

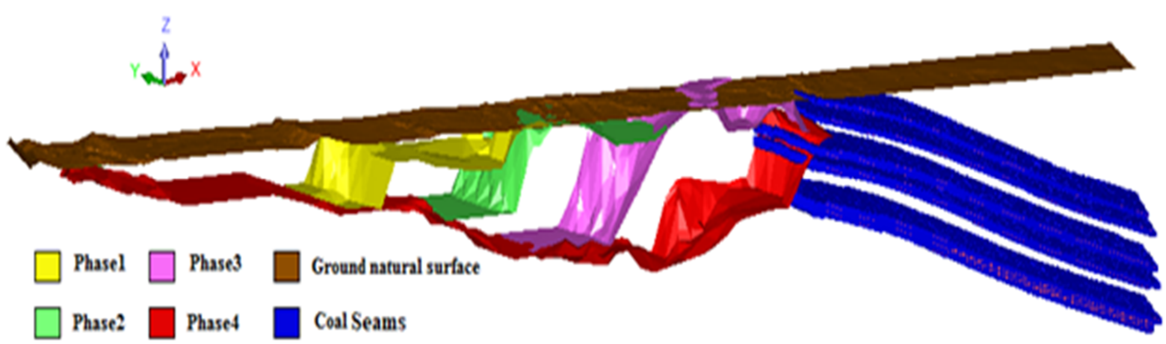



**Figure 5. Four scenarios created for the OP mining of coal seams along with the coal portions that extracted by the UG method.**

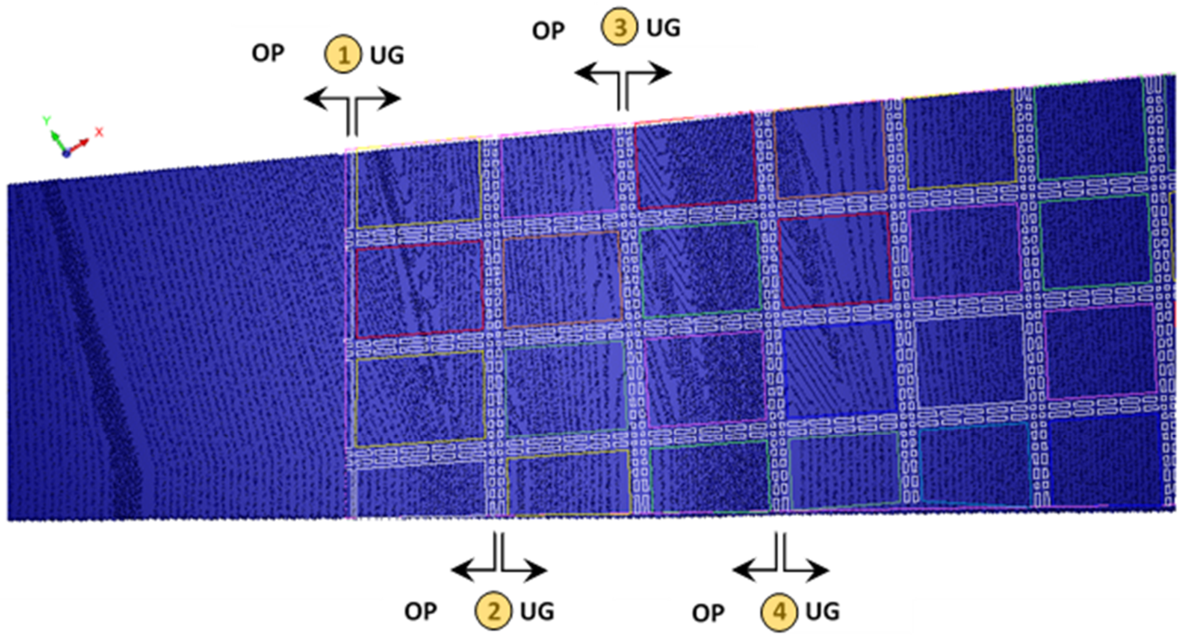



**Figure 6. The four UG scenarios that correspond to the OP developing phases (Depicted on a plan view of the M1 coal seam)**

Figure 7 depicts the numerical results in a column graph form. As it can be inferred, by developing the OP phases from phase 1 to phase 4, the profit of the OP portions have always been incremental. In the UG scenarios, by going from the second scenario toward the third one, NPV increases. However, this increment is not comparable with that of the OP portions. In case of the whole project value, the UG mining should be started whenever the OP mining of phase 4 is accomplished. In other words, in the Mazinu coal mine, the UG method cannot compete with the OP method.

**Table 4. NPVs of the OP portion, UG portion, and entire project of the four scenarios.**

| Scenario | Maximum OP depth (m) | NPV (MRials) | | |
|---|---|---|---|---|
| | | OP | UG | OP+UG |
| 1 | 70 | 1,482 | 638 | 2,120 |
| 2 | 90 | 2,052 | 638 | 2,690 |
| 3 | 140 | 2,380 | 668 | 3,048 |
| 4 | 200 | 2,526 | 640 | 3,166 |

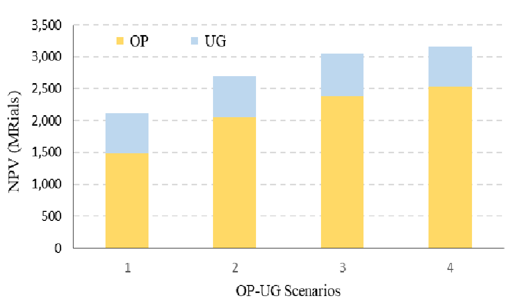



**Figure 7. NPV graph of the OP portion, UG portion, and entire project of the four scenarios.**

As a most important result, none of the stopes located between the OP phases 1 and 2 can be mined out by the UG method economically. Thus, they remain unmined if they are located in the UG portions of any scenario. In this case, no change can be observed in NPV of the UG portions that correspond to phases 1 and 2. In other words, these blocks will be economic if only they are extracted by the OP method because by developing the OP phases, the access ways to the UG stopes are shortened and they will be discounted lower. Hence, NPV of the UG portions is increased (phase 2 toward 3). In the following, due to the involvement of the valuable coal reserves between phases 2 and 3 within the fourth OP phase, the value of the UG portion is reduced again. As it can be seen in Figure 7, the rate of NPV increment of the OP phases from No. 1 to No. 4 is diminished. This is due to the incremental rate of the waste rocks that should be removed. It is also notable that in all scenarios, NPVs of the OP portions are greater than those of the UG portions.

In the present work, a scenario-based solution strategy was applied in order to determine the optimum interface between the OP and UG divisions of the Mazinu coal mine. Although this strategy can conveniently be applied for large-scale orebodies that include million numbers of blocks, it has two main disadvantages [19]:

- Firstly, the physical shape of the transition interface would be in the cast of pre-designed scenarios.
- Secondly, the optimum transition interface may be lost between two successive scenarios.

However, the results of this work indicate that in cases where the 3D surface of transition interface corresponds to the pre-optimized ultimate pit limit, a near optimal solution for the transition problem can be conceived. This notion is supported by the numerical results according to which OP progressively overwhelms the UG division economically. However, the exact optimum solution remains unrevealed because the partial progress of the UG division toward the ultimate OP space may change the entire NPV of the project. This cannot be assessed by the scenario-based solution strategy.

## 5. Conclusions

The present paper has focused on the determination of the best interface between the OP and UG operations in the Mazinu coal mine. In order to solve the problem, the scenario-based solution strategy was applied. In this regard, using the OP phases, four scenarios were created. The remaining coal portions behind every phase were considered as the UG mining areas. By calculation of NPVs of both the OP and UG divisions, NPV of the whole project was calculated for each scenario. Comparing the profitability of the whole project indicates that the Mazinu OP mine should be continued to the end of the fourth OP phase up to 200 m depth. Thereafter, the remaining coal portions should be extracted by the UG method. However, before commencement of the UG mining, the other mining alternatives such as auger mining should be evaluated for extraction of the remaining coals in the OP walls.

In addition, the results obtained indicated how the OP method could beneficially extract the coal portions that would remain unmined if they were allocated to the UG division. Besides, due to the OP progress over this portion, the access costs to the economic UG stopes were reduced meanwhile, and NPV of the UG division was increased.

Finally, although the ultimate OP limit stands as acceptable near the optimal transition interface between the OP and UG divisions, because of the essence of the scenario-based solution strategy, it was concluded that the exact optimum solution remained unrevealed. However, the applied strategy is more convenient in large-scale orebodies.

## 6. Acknowledgments

We would like to thank Mr. Nasrollahi, Mr. Lashgari, and Mr. Assari for providing us with the basic information applied in this research work.

## 7. List of symptoms

| | |
|---|---|
| $BEV$ | Block economic value ( $Rials$ ) |
| $OP$ | Open-pit mining index |
| $UG$ | Underground mining index |
| $O$ | Tonnage of coal in each block ( $ton$ ) |
| $R_M$ | Coal recovery in each mining method (%) |
| $L$ | Loss (%) |
| $Q_i$ | Calorific value of coal ( $Kcal / Kg$ ) |
| $R_{PP}$ | Power plant recovery (%) |
| $P_P$ | Electricity price ( $Rials / KWH$ ) |
| $W$ | Tonnage of waste ( $ton$ ) |
| $C_M$ | Mining cost ( $Rials / ton$ ) |
| $C_Z$ | Mining increment cost in depth direction ( $Rials / ton$ ) |
| $d$ | Dilution (%) |
| $C_H$ | Coal haulage cost from mine to the plant ( $Rials / ton.km$ ) |
| $C_D$ | Waste haulage and stack cost ( $Rials / ton$ ) |
| $C_{PP}$ | Operational cost of power plant ( $Rials / ton$ ) |
| * | Numerical coefficients in formulas (1) and (2) are used for changing the calorific value to electricity. |
| $T$ | Total scheduling periods of open-pit portion |
| $t$ | Each period of open-pit scheduling |
| $P$ | Total scheduling periods of underground portion |
| $p$ | Each period of underground scheduling |
| $B$ | The set of open-pit blocks that should be scheduled |
| $b$ | Counter of open-pit blocks |
| $S$ | Set of underground stopes that should be scheduled |
| $s$ | Counter of underground stopes |
| $\delta_t$ | Discount factor for OP periods |
| $\delta_p$ | Discount factor for UG periods |

| | |
|---|---|
| $r$ | Discount rate (%) |
| $Ash_{Min}^{OP}, Ash_{Max}^{OP}$ | Minimum and maximum bounds of allowable ash content in open-pit product (%) |
| $Ash_{Min}^{UG}, Ash_{Max}^{UG}$ | Minimum and maximum bounds of allowable ash content in underground product (%) |
| $Mill_{Min}^{OP}, Mill_{Max}^{OP}$ | Minimum and maximum bounds of power plant capacity for open-pit operation ( $ton$ ) |
| $Mill_{Min}^{UG}, Mill_{Max}^{UG}$ | Minimum and maximum bounds of power plant capacity for underground operation ( $ton$ ) |
| $x_b^t$ | Decision variables in open-pit portion |
| $y_s^p$ | Decision variables in underground portion |
| $n_b^t$ | Number of open-pit blocks that should be extracted before block $b$ |
| $m_s^p$ | Number of underground stopes that should be extracted before stope $s$ |

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# تعیین مرز بهینه معدنکاری روباز و زیرزمینی در معدن زغالسنگ مزینو نیروگاه طبس

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**چکیده:**

با توجه به افزایش تدریجی عمق لایه‌های زغالی در معدن زغالسنگ مزینو از سطح زمین، امکان بکار گیری هر دو روش استخراج روباز و زیرزمینی در این ذخایر وجود دارد. بنابراین ضرورت دارد تا مرز بهینه معدنکاری بین این دو روش تعیین گردد. مقاله حاضر بنا دارد تا مرز مورد نظر در معدن زغالسنگ مزینو را با ایجاد سناریوهای مختلف از فازهای طراحی بخش روباز و کارگاه‌های زیرزمینی متناظر با هر فاز، و مقایسه آنها با یکدیگر تعیین نماید. برای این منظور ابتدا یک مدل بلوکی اقتصادی بر اساس مقادیر ارزش حرارتی زغالسنگ‌های واقع در هر بلوک و اعمال پارامترهای فنی- اقتصادی ایجاد شد. سپس فازهای طراحی روباز با بکارگیری الگوریتم لرچ - گرو سمن بد ست آمد؛ و برنامه‌ریزی تولید کارگاه‌های زیرزمینی متناظر با هر فاز انجام گردید. در نهایت با مقایسه مجموع ارزش خالص فعلی بدست آمده برای کل پروژه (هر دو بخش روباز و زیرزمینی) در سناریوهای مختلف، بهترین گزینه از میان گزینه‌های موجود انتخاب گردید. نتایج ارزیابی‌ها حاکی از آن است که مرز بهینه معدنکاری روباز و زیرزمینی در معدن زغالسنگ مزینو منطبق بر محدوده نهایی بخش روباز با بیشینه عمق ۲۰۰ متری از سطح زمین خواهد بود.

**کلمات کلیدی:** معدن زغالسنگ مزینو، مرز بهینه معدنکاری، معدنکاری روباز، معدنکاری زیرزمینی، نیروگاه زغالسوز طبس.