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An Uncertainty-based Transition from Open Pit to Underground Mining

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ABSTRACT

There are some large scale orebodies that extend from surface to the extreme depths of the ground. Such orebodies should be extracted by a combination of surface and underground mining methods. Economically, it is highly important to know the limit of upper and lower mining activities. This concern leads the mine designers to the transition problem, which is one of the most complicated problems in mining industry. The transition problem is categorized as a strategic one and is formulated in the form of long-term production scheduling problems. This implies that the transition problem is highly affected by the uncertainties that are rooted in the quantity and quality of an explored orebody. The current study aims to evaluate the effects of geological uncertainty on transition depth. To this aim, an integer programming (IP) model was executed on different simulations of an orebody. The results indicate that the net present value (NPV) of the deterministic solution is greater than that of the basic alternative. However, the uncertainty-based solutions show that the NPV of the whole mining operation is lower than the basic and deterministic solutions mostly (more than 72% of the simulations). Nevertheless, there are some rare cases in which the NPV of the operation may increase ideally up to 2.5 % due to development of the pit bottom downward. Finally, because of a negligible difference between the average NPV of the simulations and that of basic alternative, it is expected that the primitive pit bottom would play the role of transition depth.

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1. INTRODUCTION

A combination of open pit and underground mining methods may be applied in a mining project where the shallow and deep portions of an orebody are worth mining out. In such projects, it is important for shareholders to know how much of the orebody should be extracted by each mining method. Logically, there must be a depth at which the border of each mining method is determined. It is ideal to find an optimum depth at which the maximum NPV of the entire mining project is achieved. This optimization problem, through which the optimum transition depth from open pit to underground mining is determined, is called "transition problem". Figure 1 coveys the traditional concept of transition problem schematically. As it can be inferred, there may be a depth above the level of primitive pit bottom at which the highest NPV of the whole operation could be achieved.

Determining the optimum transition depth during feasibility studies is important to mine designers, because they are eager to have a realistic estimation of the capital costs that are required for each mining portion. They emphasize the importance of the subject because of the capital cost estimation is a major part of each mining study phase [1]. It is also worth noting that mining projects are considered as capital intensive adventures.

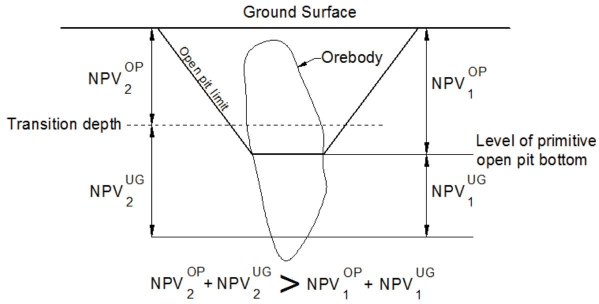

Figure 1. Traditional concept of transition problem (OP stands for open pit and UG for underground)

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In spite of the above-mentioned importance, not fully known characteristics of the orebodies put millions of invested dollars at risk. Normally, the geological characteristics of an orebody are estimated by integrating the exploration data that are gathered from a network of deep and shallow excavations. Due to the restrictive impacts of exploration costs, a limited amount of information is usually accessible for these estimations, so that geological estimations differ from the in-situ properties of mineralized zones. The existing difference between the required and available data are defined as uncertainty of data [2].

Nowadays it is a well-known fact that many mining projects have failed due to neglecting geological uncertainties [3], so that in recent mine studies the contribution of geological uncertainty to different aspects of open pit optimization problems can be traced [4-9]. The transition problem is also affected by geological uncertainty due to the increment of uncertainty amount in geological information downward.

2. LITERATURE REVIEW

Popover [10], Soderberg and Rausch [11] were the earliest researchers who have documented the early models of transition problem. The model that is presented by them determines the transition depth by balancing the open pit and underground mining costs. The mathematical form of this balancing method was used by Chen et al. [12], Chen and Guo [13]. The main disadvantage of the transition cost models is that they do not consider the grade variability through different parts of the orebodies. In 2012, Bakhtavar et al. [14] assimilated the transition problem to the open pit scheduling problem. They tried to find the optimum transition depth through maximizing the NPV of the entire mining production plans. Their efforts lead only to a two-dimensional integer programming model which should be executed on vertical sections. Hence, their method failed to present an optimum solution. Newman et al. [15] modelled the transition problem in the form of a network flow. Their method determines the transition depth by scheduling the horizontal sections of the orebody. Their method is horizontally two-dimensional and does not present an optimum solution. Dagdelen et al. [16] used a series of the Lerchs and Grossman [17] pits as transition scenarios. The authors applied a mixed integer linear programming optimizer on the successive scenarios in order to find the optimum solution. This predefining of the scenarios may cause a loss of optimality. Whittle et al. [18] used Whittle's opportunity cost approach [19] in order to embed a crown pillar between open pit and underground mining portions. They first used a graph theory approach and later modified its structure [20]. Chung et al. [21] tried to use a Mixed Integer Programming (*MIP*) model for determining the optimum transition depth. They incorporated their model with conditional simulation techniques in order to capture grade uncertainty in their study. They did not present the mathematical formulation of their model. Besides, the authors did not determine the mining method of the underground portion. In 2017, King et al. [22] applied a combination of Linear Programming (*LP*) and a rounding technique in order to provide integer solutions for transition problems. Their two-step solution approach presents near optimal solutions. Considering the importance of geological uncertainties, Macneil et al. [23] tried to solve the transition problem stochastically. They used a scenario-based approach to solve the problem. This approach does not guarantee the solution's optimality. Recently, Bakhtavar et al. [24] applied Gholamnejad et al.'s [25] stochastic scheduling model, which had been developed for open pit long-term production scheduling, in order to determine the optimum transition depth. Their economic block model, as the input data, was calculated based on Whittle's opportunity cost approach [19]. However, according to the opportunity cost approach, the transition depth is determined without optimizing the underground portion.

As it can be seen, there is not a uniform model for optimizing the transition depth between open pit and underground portions. The existing models either break the problem down into separate problems or neglect the scheduling of the underground portion. These simplified models cannot truly capture the geological uncertainty of the orebodies. The present study solves the transition problem by applying an integrated model. Furthermore, in order to control grade uncertainty, the model is executed on some equally probable realizations of the orebody. It is determined whether there are some alternatives that can provide more profits than the primitive open pit bottom or not.

3. THE STRUCTURE OF RANSITION MODEL

The transition problem is a type of long-term production scheduling during which the mining method of each block is determined, too. The borders of adjacent blocks that are to be extracted by open pit and preferred underground method play the role of transition depth. This implies that transition depth is not merely in the shape of a horizontal plane. In other words, transition depth is a ragged surface that is revealed through simultaneous production scheduling of the shallow and deep portions of an orebody. Like the common open pit scheduling problems, the main goal of transition problem is maximizing the NPV of the mining adventure. However, here the NPV of the entire operations is maximized (Equation (1)). To better understand the formulations, the notations are defined as following:

Sets and indices

$b \in B$	b is a member of block set B
$t \in T$	t is a member of time period set T
OP	stands for open pit operations

UG	stands for underground operations
p	indicator of a block under evaluation
q	indicator of a time period in which a block is under evaluation
Parameters	
R_b^{op}	Revenue of block *b* when it is extracted by open pit mining
R_b^{UG}	Revenue of block *b* when it is extracted by underground
C_b^{OP}	Mining, processing, and all costs expended to produce the salable harvest if block *b* is extracted by open pit mining
C_b^{UG}	Mining, processing, and all costs expended to produce the salable harvest if block *b* is extracted by underground mining
δ_t	Discount factor
r	Discount rate
O_b^{OP}, O_b^{UG}	Tonnage of ore in block b which may be extracted by open pit or underground method
g_b^{OP}, g_b^{UG}	Average grade of block b
G_{Max}^{OP+UG}	Maximum allowable grades of combined mining operations
G_{Min}^{OP+UG}	Minimum allowable grades of combined mining operations
$O_{Min}^{OP}, O_{Max}^{OP}$	Minimum and maximum allowable ore mining capacities of the open pit portion
$O_{Min}^{UG}, O_{Max}^{UG}$	Minimum and maximum allowable ore mining capacities of the underground portion
n_b^{t-1}	All blocks that should be removed before block b if it is mined by open pit
m_b^{t-1}	All blocks that should be removed before block b if it is mined by underground method
Variables	
$x_b^t \in \{0,1\}$	Open pit binary decision variables
$y_b^t \in \{0,1\}$	Underground binary decision variables

$$Max \sum_{b=1}^{B}\sum_{t=1}^{T}\frac{1}{(1+r)^t}\left(\delta_t(R_b^{OP}-C_b^{OP})x_b^t+\delta_t(R_b^{UG}-C_b^{UG})y_b^t\right) \tag{1}$$

Equation (1) is the objective function of the transition problem that should be optimized subject to the following physical and operational constraints:

Reserve constraint: this constraint ensures that every block is mined only once (Equation (2)). According to this constraint, only one of the two possible mining methods is assigned to each specified block (*b*).

$$\sum_{t=1}^{T}x_b^t+\sum_{t=1}^{T}y_b^t=1 \qquad \forall b\in B \tag{2}$$

Sequencing constraints: these constraints regard the physical dependencies of scheduling units (blocks) to each other in a way that is consistent with the essence of each mining method. Equations (3) and (4) represent the sequencing constraints of open pit and underground portions, respectively.

$$n_b^{t-1}x_b^t-\sum_{p=1}^{n_b^{t-1}}\sum_{q=1}^{t-1}x_p^q\le 0 \qquad \forall b\in B \ \&t\in T \tag{3}$$

$$m_b^{t-1}y_b^t-\sum_{p=1}^{m_b^{t-1}}\sum_{q=1}^{t-1}y_p^q\le 0 \qquad \forall b\in B \ \&t\in T \tag{4}$$

Suppose in Figure 2 that block b is to be mined by either open pit or underground method. Thus, the precedence of blocks' removal differs for each case.

Quality constraint: when the open pit and the underground portions of an orebody are extracted simultaneously, the extracted ore can be mixed and used in process plant. Thus, the quality of all extracted blocks during each mining period should be controlled within a range. However, the required quality may be provided form just one portion in some periods. Equations (5) and (6) define the upper and lower bounds of the required quality ($\forall t\in T$), respectively.

$$\sum_{b=1}^{B}(O_b^{OP}g_b^{OP}x_b^t+O_b^{UG}g_b^{UG}y_b^t)\le G_{Max}^{OP+UG}\left(\sum_{b=1}^{B}(O_b^{OP}x_b^t+O_b^{UG}y_b^t)\right) \tag{5}$$

$$G_{Min}^{OP+UG}\left(\sum_{b=1}^{B}(O_b^{OP}x_b^t+O_b^{UG}y_b^t)\right)\le\sum_{b=1}^{B}(O_b^{OP}g_b^{OP}x_b^t+O_b^{UG}g_b^{UG}y_b^t) \tag{6}$$

Capacity constraint: the total amount of required ore should be within a predefined range (Equation (7)). According to this equation, the possible lack of extracted ore from each portion can be compensated for by the other portion, so that the upper and lower bounds are satisfied.

$$O_{Min}^{OP}+O_{Min}^{UG}\le\sum_{b=1}^{B}(O_b^{OP}x_b^t+O_b^{UG}y_b^t)\le O_{Max}^{OP}+O_{Max}^{UG} \tag{7}$$

$$\forall t\in T$$

As mentioned previously, constraints (2) to (7) imply that the mining activities in upper and lower portions are executed simultaneously. However, in some mining periods mining activities may be halted in one portion and the required materials be extracted from the other portion.

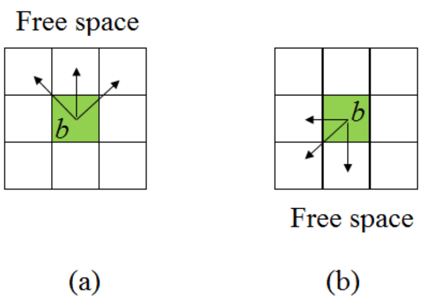

Figure 2. Precedence of bocks' removal in (a) open pit method, (b) underground method

4. PROBABILITY OF NPV IMPROVEMENT

Conditional simulation is a generally accepted method for evaluation of geological uncertainty. According to this method, some equally probable geological models of orebody should be prepared [26]. Using the economic factors, these geological models are converted to the economical block models. Then, a deterministic optimization model of the aimed problem is executed on every block model. This way, a range of solutions are achieved, which can be compared with each other or with a basic one.

In this study, the probability of NPV improvement is evaluated by comparing the achieved solutions from integrated transition model with a basic alternative. It is determined how portion of solutions present an NPV greater than this alternative. The basic alternative is defined as the bottom of optimized pit limit, which has been determined previously. According to the basic alternative, underground mining is commenced whenever the open pit mining is terminated. In other words, the predefined open pit bottom plays the role of transition depth. In this case, the NPV of the whole mining operation is calculated by summing the NPV of open pit and underground portions, which are derived from separate production scheduling of each portion. In contrast to this method, the integrated transition model calculates the NPV of the entire mining operation by scheduling the upper and lower portions simultaneously. As a case in point, the Anguran lead and zinc deposit in Iran, which is currently extracted simultaneously by open pit and cut and fill methods can be cited.

By executing the proposed integrated model on all simulations, if the majority of the solutions present a NPV greater than the total NPV of the basic alternative, the primitive transition depth should probably be displaced in order to provide more profits (Figure 3). It seems that selecting an alternative the NPV of which is close to the mean of all values would be reasonable, especially when the suggested displacements are in the same direction. On the other hand, if most of the solutions present minor NPVs (Figure 4), the displacement of the primitive transition depth will not probably result in higher profits. It seems that the primitive NPV has been overestimated. In case of considering the geological uncertainty, a probabilistic transition zone can be determined. Then, the probability of transition between two elevations can be defined based on the solutions which are a portion of whole transition zone and locate between these elevations. The probability of transition can be determined with a confidence level. In this paper, the probability of NPV improvements are mainly focused.

It is also worth noting that depending on the physical configurations of the solutions (3D transition surfaces), which correspond to the numerical solutions of the problem (decision variables), the predefined open pit bottom may be shifted up or down to a more profitable transition depth

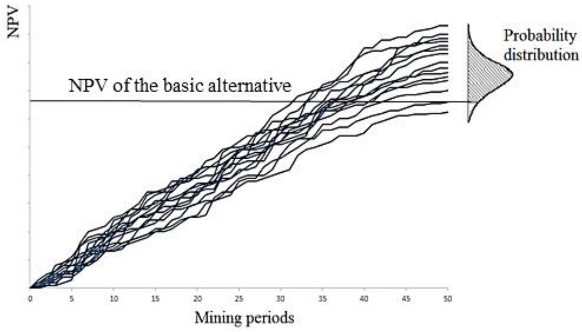

Figure 3. The transition alternatives probably provide more profit than the basic one

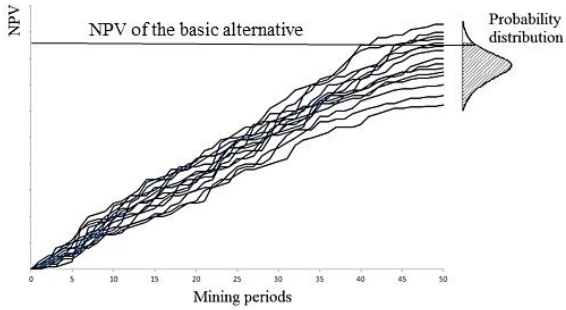

Figure 4. The transition alternatives are not probably more profitable than the basic one

(Figure 5). This variability of the physical solutions around the pit bottom is in contrast with the traditional notions. Because, in case of encountering transition problems in a deterministic form, the transition depth is expected to be located above the primitive pit bottom. However, in the stochastic form of the problem, the transition depth may be located beneath the primitive pit bottom. In other words, the open pit is deepened as a result of geological uncertainties. This occurs in simulations in which the block values enhance due to the higher grades that may be estimated for them. The more valuable ore blocks can remove more waste rocks so that the pit bottom and, consequently, the transition depth are deepened. This point of view renews the traditional thoughts about the transition depth.

Figure 6 delineates the approach of uncertainty- based optimization for transition problems. In the current paper, a number of realizations of the orebody are created at first. Then the integrated model is executed on every realization. In the following, the probability of improvement is calculated by comparing the numerical solution of basic alternative with the simulated ones.

If the possibility of improvement is greater than a desired value (here fifty percent), then the primitive transition depth should be displaced to a better location. Otherwise, the primitive transition depth remains unchanged. It means that the open pit bottom plays the role of transition depth.

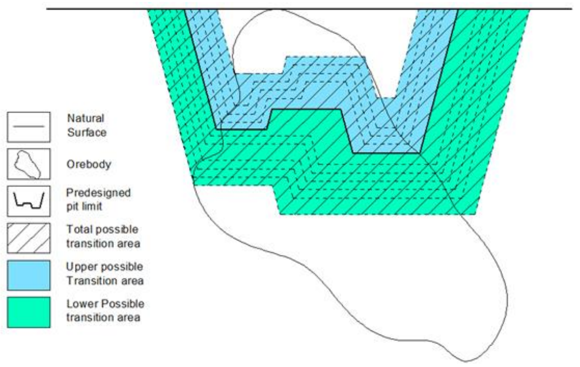

Figure 5. Various transition alternatives that may occur due to geological uncertainty

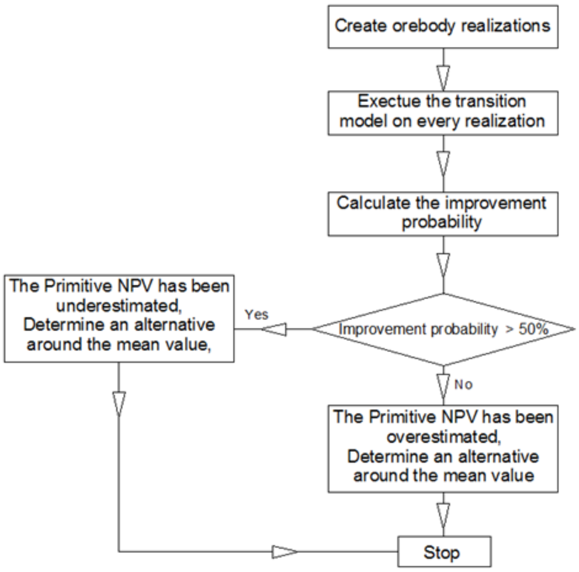

Figure 6. Uncertainty-based optimization of transition depth

5. EMPRICAL RESULTS AND DISCUTION

In order to evaluate the effects of grade uncertainty on transition depth, the transition model was executed according to the proposed approach on a hypothetical block model. The raw data of the hypothetical model was extracted from a critical zone of a real iron deposit, which was potentially capable of transition. At the first stage, a block model was created according to the conventional Ordinary Kriging (OK) method. The NPV of the primitive optimization process was considered as the basic solution. The above-mentioned formulations of the integrated transition model were executed on this model and a deterministic solution was achieved. Then, 12 realizations of the case study were simulated using the Sequential Gaussian Simulation (SGS) method. The same integrated model was executed on each realization. Whenever a scheduling model is run, the transition depth is revealed between decision variables of the open pit and underground portion. The numerical results of objective function for the basic alternative, deterministic solution, solution of all realizations, and their average are illustrated in Figure 7.

The results indicate that when the integrated model is executed in a deterministic form, the NPV of the whole mining operation is enhanced about 0.15% (Table 1). However, compared to the deterministic and basic alternatives, the uncertainty- based solutions indicate that more than 72% of the transition alternatives present lower NPVs (the improvement probability is less than 28%). This implies that encountering the transition problems according to the traditional scheduling problems may show a deceptive increment in NPV of the entire mining operation. The average NPV of the realizations is less than that of the basic alternative, although their difference is negligible (<0.1%).

On the other hand, the graphical results show that scenarios 1, 4, 6, 7 and 12 trespass toward the primitive open pit area (Figure 8). However, only scenarios 1 and 7 present higher NPV values in contrast to the basic alternative. This disharmony occurs due to the grade variability of different

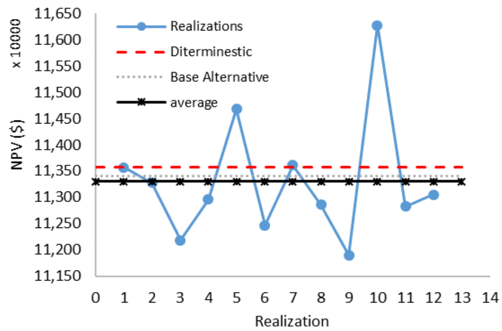

Figure 7. Results of integrated transition model

TABLE 1. Comparing the solutions with the results of expected and basic alternative

Real.	NPV($)	Relative comparison (%)	
		Basic alt.	Expected
1	113,570,020	+0.15	-
2	113,280,301	-0.11	-0.26
3	112,181,308	-1.08	-1.22
4	112,957,303	-0.40	-0.54
5	114,680,293	+1.12	+0.98
6	112,470,306	-0.83	-0.97
7	113,615,299	+0.18	+0.04
8	112,861,304	-0.48	-0.62
9	111,895,310	-1.33	-1.47
10	116,276,283	+2.53	+2.38
11	112,828,304	-0.51	-0.65
12	113,052,303	-0.31	-0.46

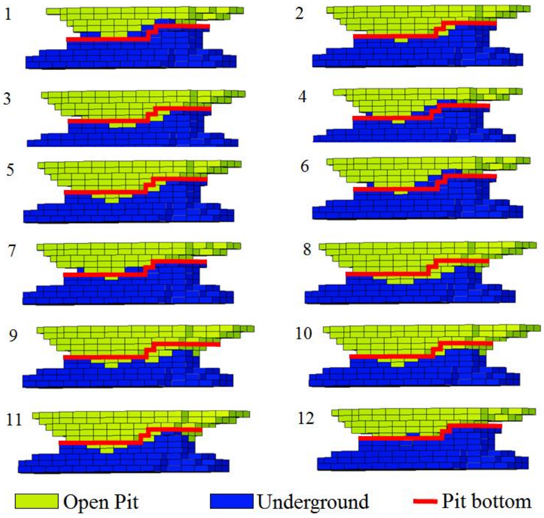

Figure 8. Graphical results of different realizations

scenarios. It can be seen that the majority of scenarios trespass toward the underground portion. Most of them present lower NPV values in contrast to the basic alternative. However, the two highest values exist among these series. This implies that due to the grade uncertainty it is viable for primitive open pit bottom to be extended downward beneficially. In this case, the NPV of the entire mining operations may increase ideally up to 2.5%.

Compared to similar studies conducted by Newman et al. [15] and Chung et al. [21]; this paper presents a ragged surface as the border of open pit and underground mining activities instead of a horizontal plane. Besides, it was shown that the transition alternatives could fluctuate around the primitive pit bottom when the uncertainties are considered.

6. CONCLUSION

When a combination of open pit and underground mining methods is applied to extract an orebody, an optimum transition depth should be determined between them inevitably. On the other hand, it is ideal for mining complexes to extract the shallow and deep portions of an orebody with the highest profit. Having a comprehensive production schedule of the entire orebody can determine the border of mining activities meanwhile providing them with a perspective of total future mining profits. Incorporating the resources' uncertainties into such scheduling problems provides more realistic results.

The present study incorporated the grade uncertainty into the transition problem in order to capture the effects of such uncertainty on the transition decision. In this regard, an integrated scheduling model was executed on some realizations of an orebody as a transition model. The results were noticeable because although the deterministic solution of the transition problem uplifts the primitive open pit bottom for enhancing the total NPV, the probabilistic solutions indicate that the highest NPV may be achieved by developing open pit bottom downwards. Furthermore, it can be concluded from the results that the NPV of the whole mining operation is probably less than the NPV of the basic alternative. However, because of a negligible difference between the average NPV of the realizations and the basic alternative, the primitive pit bottom can be considered as the transition depth.

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Production Scheduling

چکیده

ذخایر معدنی برزگ مقیاسی وجود دارند که از سطح تا اعماق بسیار زیاد زمین گسترش یافته اند. چنین ذخایری را باید با ترکیبی از روش های معدنکاری سطحی و زیرزمینی استخراج نمود. به لحاظ اقتصادی، دانستن مرز هر یک از فعالیت های معدنکاری سطحی و زیرزمینی بسیار مهم است. این دغدغه باعث می شود که طراحان معدن به سمت مسأله گذار که یکی از پیچیده ترین مسائل در صنعت معدنکاری می باشد سوق داده شوند. مسأله گذار در زمره مسائل استراتژیک تقسیم بندی شده و به شکل مسائل برنامه ریز تولید بلند مدت فرمول بندی می گردد. این بدان معنی است که مسأله گذار به شدت تحت تأثیر عدم قطعیت هایی است که ریشه در کمیت و کیفیت ذخیره معدنی اکتشاف شده دارند. مقاله پیش رو در نظر دارد تا تأثیر عدم قطعیت های زمین شناسی را بر مسأله گذار ارزیابی نماید. برای این منظور یک مدل برنامه ریزی عدد صحیح بر روی شبیه سازی های مختلف از یک ذخیره اجرا شد. نتایج این بررسی نشان می دهد که NPV بدست آمده برای حالت قطعی بیشتر از NPV مربوط به گزینه پایه است. هرچند، جواب های مبتنی بر عدم قطعیت نشان می دهند که NPV کل فعالیت های معدنکاری کمتر از جواب های پایه و قطعی هستند (بیش از ۷۲ درصد جواب ها). با این حال، اندک مواردی نیز وجود دارند که در آنها NPV فعالیت معدنکاری ممکن است با توسعه کف پیت به سمت پایین بطور ایده آلی تا ۲/۵ درصد افزایش یابد. در نهایت، بخاطر وجود یک اختلاف قابل اغماض بین میانگین NPV شبیه سازی ها و NPV گزینه پایه، انتظار می رود که کف پیت نقش عمق گذار را ایفا نماید.

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