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Production scheduling of sublevel caving underground mining method using a conceptual linear modeling and considering ventilation constraints

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ABSTRACT

The increasing global demand for minerals, driven by industrial and technological advancements, has led to a shift towards exploiting deep underground deposits as surface deposits become depleted. This shift has prompted a significant focus on underground mining methods, particularly caving methods, which involve the controlled collapse of ore to create a void for further extraction. However, despite the growing adoption of these methods, there is a noticeable lack of comprehensive studies related to production planning for such operations. To address this critical gap, our research proposes a linear production planning model aimed at maximizing profit in the context of underground caving methods. The model is designed to incorporate various constraints, including processing plant capacity, mining limitations, and mine ventilation system requirements. Although main contribution of this paper lies in comparing the proposed model with previous studies and also it is possible to apply the proposed model to all mineral deposits that are suitable for mining using the sublevel caving method, but unlike previous models, this comprehensive approach is intended to optimize profits across different periods, offering a new perspective on production planning in the mining industry. By integrating these crucial factors into the production planning model, our research aims to enhance overall efficiency and profitability in underground mining operations. This innovative approach could potentially revolutionize the way mining companies plan and execute their production strategies in the challenging environment of deep underground mining. In addition to these items, in this study, the ventilation constraint is defined to provide enough air volume for operation. This constraint can increase the safety of the operation, which is not considered in many studies.

KEYWORDS

Sublevel Caving, Production Planning, Linear Programming, Optimization, Underground Mining

I. INTRODUCTION

Mines require a consistent and organized flow of minerals through various processes. To achieve a reliable and high-quality flow, it is essential to plan a production schedule that is suitable and adaptable to the existing conditions. This scheduling should be comprehensive, covering various periods, and optimized for efficiency.

When transitioning from open-pit to underground mining, various calculations are carried out to decide which part of the ore body should be extracted using surface mining methods. This decision is based on economic and technical factors. As a result, ore bodies situated beneath the ultimate pit limit are mined using underground methods.

Several mines around the world are produced minerals by open pit method. Some of them reached to ultimate pit limit and should transition to underground methods because of remain ore body and processing plants that available on mine sites. Additionally, this can increase the period of mining to obtain maximum financial efficiencies.

Sublevel caving is a highly productive underground mining method that can rival open-pit mining techniques in terms of economic efficiency and production rates, particularly for large metal deposits. For this method to succeed, the hanging wall must be suitably caveable, and the ore body must be located at a significant dip angle with temporary self-support capability. It is worth noting that using this underground method can lead to ground surface subsidence, depending on the cave angle of the hanging wall.

Valuing mining projects is significant and complex because of their considerable differences from other industries based on unreliable characteristics and associated uncertainties in sample data. Also, the profitability of mines is controlled mainly by the global

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price of goods, which is random and cannot be controlled over time. The result is an industry where decisions must be made with high levels of uncertainty (Maybee and Yana, 2017).

According to Hall (2007), studies on project strategy showed that mine plans are unlikely to be optimized entirely because of dependency on various parameters such as operation strategies, cut-off grade, and grade properties that are not fully accounted for in mine scheduling optimization. The rock mass behavior in underground stops is one of these parameters that Saeidi (2015) investigated.

Also, in UG (Underground) mines, block models associated with economic information can be used to identify zones with economic values. It should be noted that in UG, adverse to OP (Open Pit Mines), in-situ ore is considered a mineral repository, and the objective of mine planning is to minimize waste extraction (O'Sullivan and Newman, 2015).

The mine planning can be categorized into three classes without differences between OP and UG as follows:

- Long-term planning (for all of mine ages)
- Mid-term planning (annually or 1 to 3 months)
- Short-term planning (monthly, weekly, and daily)

Long-term planning is a strategic plan for a mine that illustrates mining objectives for a period longer than one year. These plans include all mine ages, even those determined based on long-term planning. The long-term plan is divided into smaller planning periods that characterize technical conditions. In this type of planning (mid-term), mining objectives are determined more precisely, but it is still an estimation.

Mid-term plans are divided into smaller plans called short-term planning. In these types, operation properties from month to day are determined. Because of the accuracy of short-term plans, even the ore destination should be identified (Campeau and Gamache, 2020).

Mathematical production planning has been utilized for UG scheduling for several decades now. For instance, mixed integer programming was used to optimize mine planning in the 1960s, and it could potentially optimize production scheduling problems in OP and UG mines. The main issue for long-term production scheduling in UG is related to the many required variables in the Mixed Integer Programming (MIP) model, which resulting in complexity in solving the model. The necessary time to solve the model was incredibly increased by increasing the number of variations. In several cases, using MIP is ignored according to the long-time solving process (Nehring et al., 2010). Maybee et al. (2009) conducted a study on the effects of strategies on UG projects. They determined that even minor fluctuations in the rate of development can have a significant impact on the value of mining projects.

II. SUBLEVEL CAVING METHOD

Sublevel caving (SLC) has gained popularity for its application in hard rock formations due to its potential for high production rates and cost-effective operations. Recent technological advancements and improved approaches to designing, planning, and modeling SLC operations have enabled its extension to greater depths within rock formations, even in the presence of more significant geotechnical challenges (Darling, 2011). In SLC (Sublevel Caving), fragmented ore is extracted from the ends of drifts. Once the ore is removed, waste and roof rocks are deliberately allowed to collapse, which in turn initiates the caving process. This controlled caving process enables efficient extraction of the ore from the deposit while minimizing the need for extensive support structures. Fig. 1 presents the geometry and shape of a schematic sublevel caving method.

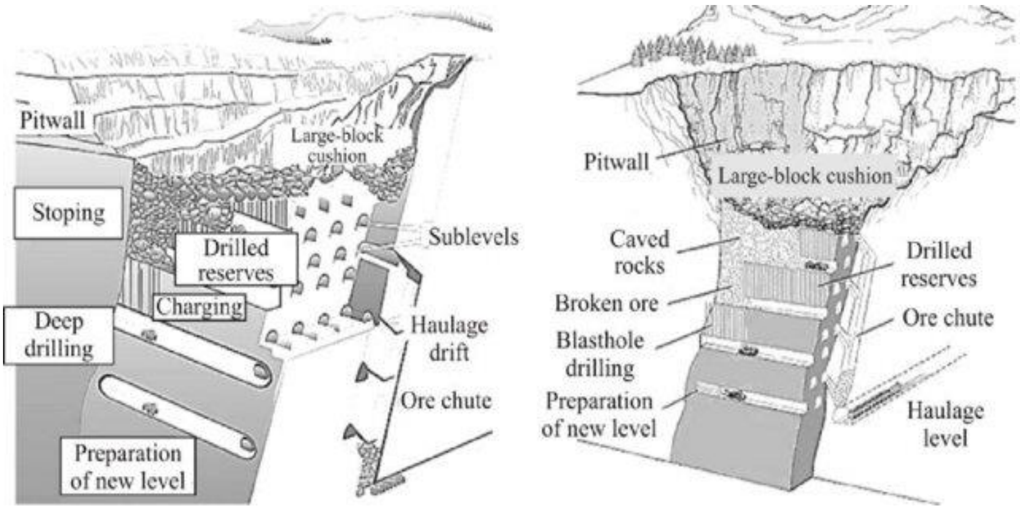

Fig. 1. Schematic operations of the sublevel caving method (Konurin et al., 2009)

The following list provides a detailed explanation of the current condition of SLC and the specific parameters that need to be taken into account during the process of design and planning.

- In the SLC, the sublevel interval is 6 to 20 m.
- The burden in fan drills is 1.2 to 1.8 m.
- The direction of advancement is from hanging wall to footwall
- It is available to work in several sublevels
- The dilution and extract rate of ore should be considered
- The dilution allowed in the range of 10 to 35 percent
- The cut-off grade is used to determine the next drilling cycle
- Ventilation plays a vital role in SLC
- The production rate should be in the range of 20 to 40 tons per worker shift.
- The ore recovery varies between 10 and 80 percent.
- The ore drawing should be accurately controlled.
- Fragmented rock size should be controlled.
- The bin volume should be accurately considered.
- The haulage capacity is a crucial factor in operation.
- The advancement rate is limited by the number of blasts and working hours.

III. LITERATURE REVIEW

This section conducted a thorough review of mining production planning and scheduling. Song et al. (2013) provided a comprehensive summary of real-time optimization of production in underground mining. Additionally, Nhleko et al. (2018) examined the optimization of stop boundaries in underground mining, while Newman et al. (2010) reviewed the application of operations research in mine design. However, these studies primarily focus on optimizing block extraction sequences and operational resources.

Some researchers have attempted to optimize mine profitability by utilizing financial tools. For example, Samin and Poulin (1998) proposed a valuation model for mines by using decision trees and DCF tables. Kazakidis (2001) used put-and-call barrier options to achieve a flexible valuation of an underground mine. Additionally, employing Monte Carlo and considering two mining sequences makes it possible to inject flexibility into the mine plan and alter decisions based on the results. Rodriguez and Padua (2005) utilized portfolio optimization methods in the oil exploration industry to maximize company value.

Decision variables were usually assumed to be continuous in the earliest mathematical models for underground mine planning (Chanda, 1990; Jawed, 1993). It seems that Trout (1995) is the first one to use mixed integer planning in underground mines and develop a multi-period production plan for a copper mine in Australia. Winkler (1996) conducted production planning in an underground coal mine to minimize primary and variable costs, but this model was included only for one period. In a different study, Winkler (1996) introduced production planning for an underground coal mine to minimize fixed and operating costs using MILP. Nehring (2006) presented a model based on the Trout (1995) study and added a filling constraint, making the model applicable to the sublevel stoping method.

Little et al. (2008) used the modified Nehring model and added some strategies to reduce number of variables in the model and decrease solving time. Topal (2004) developed a model to optimize production planning with the MIP method to minimize production deviations in an iron ore large-scale sublevel caving mine. Carlyle and Eaves (2001) used integer programming to prepare the production plan for the Stillwater mine. Smith et al. (2003) endeavored to present a model with constraints like sequence, capacity, and minimum production requirements. Rahal et al. (2003) utilized integer programming for long-term planning in a block caving mine. Sarin and West-Hansen (2005) tried to maximize the NPV of a coal mine operated by long wall, room, and pillar mining methods. Also, this planning included some penalties to avoid operational irregularities.

Brazil and Thomas (2007) optimized the shape of the loading ramp in a sublevel stoping mine. Their model also included constraints on the minimum radius required for turning, mineral access restrictions, and other usual restrictions. McIsaac (2005) planned the production of a polymetallic deposit with different geological characteristics, thus requiring different mining methods using MIP to maximize cash flow. This program had a total of 1200 variables. In this article, there is no mention of guaranteeing the optimality of the answer. Nehring et al. (2010) presented a classical MIP model for optimal production planning of a sublevel stoping operation. They offered a new formulation that significantly reduced the time needed to solve without changing the results and preserving all constraints. The objective function seeks to maximize the cash flow of all considered activities.

Maybee and Yana (2017) also tried to optimize the underground mining project's value by adjusting the return rate on investment. Hall (2007) used the linear programming method to maximize the project value optimally using the hill of value (HoV) method. This method also considered strategic decision variables and created a realistic model that could change mining strategies. Brickey (2015) also incorporated ventilation constraints into production planning and applied his model to a gold mine mined by various methods. The only variable used was a binary variable related to performing an activity at a particular time. The objective function has also been to maximize the net present value of the entire mining project.

Carpentier et al. (2016) introduced a two-stage integer stochastic mathematical programming model for the long-term production planning of underground mines, which could consider geological uncertainty as a grade risk. Sharma (2015) discussed optimizing the production planning of an underground mine to maximize NPV and take into account geological and ventilation constraints. Saeedi (2015) has also examined the sequence of extraction of stopes, considering the limitations related to the time-dependent behavior of rocks. O'Sullivan and Newman (2015) proposed a production planning model for an underground lead and zinc mine in Ireland that was mined using three different methods. Their objective was to maximize metal production. The limitations considered for their model included the extraction sequence and the filling sequence.

Foroughi et al. (2019) introduce stopes layout design and production planning as the main stages of determining the profitability of an underground mining project. To optimize these two problems, they developed a multi-objective integer programming model for extracting operations from sublevel stoping. They used a non-dominated screening genetic algorithm (NSGA-II) to solve the objective function. Sirinanda et al. (2018) designed and optimized ore access tunnels as an optimization problem. This paper presented an algorithm for the optimal placement of the intersection to maximize the NPV, and this work had to be done while the two working faces were advancing. Astrand (2018) has studied the automation process of short-term mine planning, presented the fleet planning problem, and then presented a flow shop environment to model the mining production planning problem.

Campeau and Gamache (2020) presented an optimization model for short-term (weekly) planning in their paper. They used a non-exclusive mixed integer program to create optimal scheduling in a short-term time horizon. The objective function was defined as maximizing the extracted tonnage in the shortest possible time while keeping the minimum possible amount of the mineral's tonnage that can be fed to Asia in Sinehkar. Gligoric et al. (2020) also considered the uncertainty related to the metal price and operating costs in the production planning of a small underground mine that uses the room and pillar method. Mousavi and Sellers (2019) used the in-mine recovery (IMR) method in production planning and showed that combining this method with the usual extraction methods from underground mines can improve NPV.

A small number of underground mines are extracted by sublevel caving worldwide. Among the most famous of these mines is the Kiruna mine in Sweden. Almost all the studies conducted on the planning of underground production by subgrade destruction have been on this mine.

Almgren (1994) considered a time frame of one month using the placement of machines as the main mining units, and therefore, for 5-year planning, the model had to be run 60 times. Topal (1999) and Dagdelen et al. (2018) solved one-year subproblems iteratively to obtain production planning for five—and seven-year horizons. Kuchta et al. (2004) also considered the decisions related to the placement of machinery in the Kiruna mine. They tried to solve these models by changing the previous models and removing several decision variables. Their model sample included a five-year time horizon and three ore grades. They managed to achieve a near-optimal solution.

Newman and Kuchta (2017) modified the model of Kuchta et al. (2004) by using an innovative method of model aggregation to target the original model search process. Also, Newman et al. (2007) considered the underground production planning problem of the Kiruna mine using mixed integer linear programming for two levels of machine and production block placement. They showed that their model had a better production margin in all time horizons and for all ore grades. However, their planning was challenging to achieve due to the size of the mine and the number of time horizons. Martinez and Newman (2011) presented a mixed integer programming model for long-term and short-term production planning in the Kiruna sublevel caving mine. Their model minimizes the deviation from monthly production values. They stated that due to the mathematical structure of the model and its relatively large size, cases with a time horizon of about one or two years cannot be solved. To optimize their model, they used an innovative decomposition method that achieves better solutions faster.

Musingwini et al. (2003) defined just-in-time (JIT) development through parallel planning to re-evaluate mining progress rates. They concluded that JIT development can increase the NPV of the Shabani mine (an underground mine mined in Zimbabwe). They performed correlation and regression analyses between buffer time, buffer mineral reserves, ore deposits, and advances.

IV. LINEAR PLANNING MODEL

Based on research and studies conducted in UG production planning, mine planning can be divided into two separate sections as follows:

A) the production planning and the priority of extraction stops

B) the scheduling of ore extraction for each stop

Section A refers to mid-term planning, and the other is related to short-term planning.

In addition to the items stated above, the following assumptions must be considered for production planning in SLC.

A) The Extraction of ore should be smaller than the specified burden. If the extraction is bigger than the burden, it may lead to interlocking ore in the waste.

B) It is assumed that the needed assets, such as drilling, charging, loading, and hauling machines, are available at all stops and that they are not required to be transferred between stops.

C) The shape of the ore body and latitude and longitude expansion must be considered, as these factors significantly influence product planning and mining operations.

Most production planning methods and models involve scheduling mining operations such as development, drilling, blasting, loading, hauling, and filling based on concepts of earliest starting time and latest start time (2008). However, this planning type is unsuitable for SLC because filling the spans is not performed. Additionally, the drilling, blasting, loading, and hauling period is shorter than the development period in SLC. Furthermore, these operations in SLC are conducted periodically and consecutively, unlike block caving and sublevel stoping methods, leading to a significant increase in decision variables.

The parameters are determined after each formula based on the schematic picture illustrated in Fig. 2.

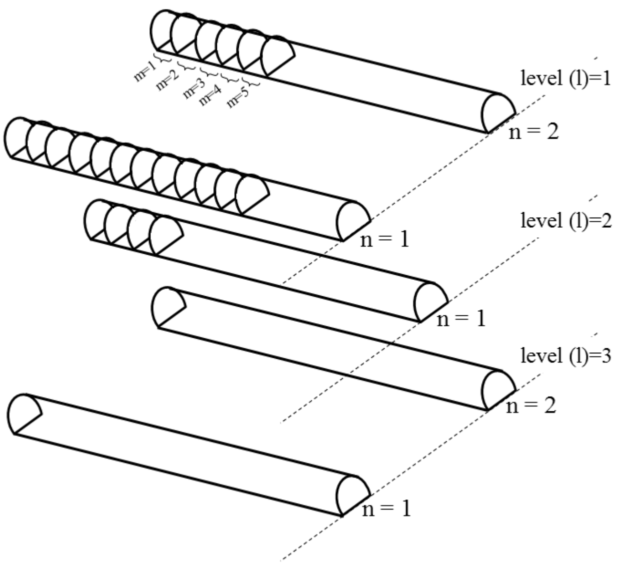

Fig. 2. A schematic of the SLC method

The binary variable presented here serves a specific purpose in the mining operation model. It is identified as follows:

If the ring number "*m*" from stope "*n*" in level "*l*" is extracted in time "*t*" then $xm^t_{n,l} = 1$, else $xm^t_{n,l} = 0$.

Here, l (*l*=1, ..., *L*) is the number of levels, *t* (*t*=1, ..., *T*) is the number of periods, *n* (*n*=1, ..., *N*) is the number of stopes at a level and *m* (*m*=1, ..., *M*) is the number of rings. Hence $m^t_{n,l}$ would be nominator of ring m from stope *n* at level *l* at time *t*, and $xm^t_{n,l}$ would be Binary decision variable for extracting the *m* ring.

A. OBJECTIVE FUNCTION

In mining operations, objective functions are identified in various types, such as maximizing production, NPV, or minimizing costs, and equipment time to repair. The assumed model defines the objective function as maximizing operational profit.

$$MaxZ = (TOm^t_{n,l} \times gm_{n,l} \times P^t \times xm^t_{n,l}) - (TWm^t_{n,l} \times C^t) \quad (1)$$

Here, $TOm^t_{n,l}$ is Amount of ore extracted from a ring, $gm_{n,l}$ is Average grade of ring *m*, P^t is Profit of extracting 1 ton of ore at time *t*, $xm^t_{n,l}$ commented befor, $TWm^t_{n,l}$ is amount of waste extracted from a ring, and C^t is costs of extracting 1 ton of waste at time *t*.

This objective function is defined to calculate the profit of extracting ore from each ring of stopes in a specific time by subtracting the costs of removing waste.

Extracting diluted ore from a mine can result in higher operating costs. This is because the increased volume of extracted materials leads to higher hauling and processing costs. Diluted ore requires additional processing to separate the valuable minerals from the waste rock, which increases the overall processing costs. Additionally, the increased volume of materials requires more transportation resources, leading to higher hauling costs. It is possible to assume that the profit of extraction of each ring is the coefficient of the object function. Therefore, the variable is defined as the extraction of a ring, including ore and waste. The cost of extraction of additional waste should be added to the formula and calculated that can be subtracted from the object function.

The tonnage of extracted waste could be calculated as a function of rock mechanics conditions. For this aim, according to the fracture conditions of the hanging wall and its fragmentation caused by subsidence, a relation to determine the tonnage of extracted waste could be identified for each ring and level.

B. CONSTRAINTS

The first constraint is defined as the acceptable tonnage for the plant. This constraint prepares the specific amounts of ore that should transfer to the plant in a given period.

$$T^t_{\min} \le \sum_{m^t_{n,l}}^{m^T_{N,L}} \left((TOm^t_{n,l} + TWm^t_{n,l}) \times xm^t_{n,l} \right) \le T^t_{\max} \quad \forall t = 1, \dots, T \quad (2)$$

Here, $T^t_{\min}$ is minimum acceptable tonnage of plant, $TOm^t_{n,l}$, $TWm^t_{n,l}$ & $xm^t_{n,l}$ expressed before, and $T^t_{\max}$ is maximum acceptable tonnage of plant.

The suitable grade for the plant is the constraint that guarantees feed with a properly equal grade and the lowest fluctuation each time. This aim is obtained by a feed that is varied between the minimum ($G^t_{\min}$) and maximum ($G^t_{\max}$) acceptable grade for the plant.

$$G_{\min}^{t} \leq \sum_{m_{n,l}^{t}}^{m_{N,L}^{T}} \left(\frac{TOm_{n,l}^{t} \times gm_{n,l} \times xm_{n,l}^{t}}{(TOm_{n,l}^{t} + TWm_{n,l}^{t}) \times xm_{n,l}^{t}} \right) \leq G_{\max}^{t} \quad \forall t = 1,\ldots,T \tag{3}$$

The amount of ore deposit is another constraint that ensures each ring is ultimately extracted once. This constraint allows a ring to be extracted just once during all extraction periods and is defined as 1 if the ring is extracted and equal to zero if the ring is almost in-situ or not hauling.

$$\sum_{t=1}^{T} xm_{n,l}^{t} \leq 1 \qquad \forall t \tag{4}$$

The extraction capacity constraint defines the amount of ore production during each period that should be between the minimum and maximum amounts. These amounts are a function of the summation of mining equipment capacity. Therefore, all volumes of extracted ore and waste are considered.

$$TR_{\min}^{t} \leq \sum_{m_{n,l}^{t}}^{m_{N,L}^{T}} \left[\left(TOm_{n,l}^{t} + TWm_{n,l}^{t} \right) \times xm_{n,l}^{t} \right] \leq TR_{\max}^{t} \qquad \forall t \tag{5}$$

Here, $TR_{\min}^{t}$ is minimum extract capacity of mine and $TR_{\max}^{t}$ is the maximum extract capacity of mine.

Furthermore, it is important to consider this constraint for every stope. This means that the amount of material that can be extracted from each stope during each period is limited.

$$0 \leq \sum_{m_{n,l}^{t}}^{m_{N,L}^{t}} (TOm_{n,l}^{t} + TWm_{n,l}^{t}) \leq TR_{\max(n)}^{t} \tag{6}$$

Here $TR_{\max(n)}^{t}$ is the maximum extract capacity of each stope.

The extraction sequence constraint is defined to limit the model's extraction of rings for HSE aims. To achieve this aim, the rings located at the upper level should be extracted before being placed at the lower levels as soon as possible.

$$xm_{n,l}^{t} - xm_{n,l+1}^{t} \leq 1 \qquad \forall m \tag{7}$$

The ventilation constraint ensures that there is enough air volume for each active stop. This constraint can limit the operation of active stops due to the limitations of air conditioning machines. The constraint consists of two parts: the first part is the constant needed air for the accessible tunnel network, and the second part is the variable needed air for operating and active stops. The total needed air can vary between the minimum volume required ($V_{\min}^{t}$) for operation and the maximum capacity ($V_{\max}^{t}$) of the ventilation machine. This information is presented as follows:

$$V_{\min}^{t} \leq V_{overall} + \left(\sum_{n=1}^{N} \sum_{l=1}^{L} \left[V_d \times \left(\left(M_{n,l}^{t} - m_{n,l}^{t} \right) \times d_m \right) \times xm_{n,l}^{t} \right] \right) \leq V_{\max}^{t} \qquad \forall t \tag{8}$$

Here, $V_{\min}^{t}$ denotes the minimum volume of air needed, $V_{overall}$ is volume of air needed for tunnel systems, V_d is volume of air needed for ventilate of 1 m^3 of tunnels, d_m is length development of each ring, and $V_{\max}^{t}$ is Maximum Volume of air needed.

In this equation, the term $M_{n,l}^{t} - m_{n,l}^{t}$ expresses the stope length (in meters) and shows the maximum number of rings in a stope with a minus active ring.

Also, if the operation faces worker limitations, the worker constraint should be added to the model because of the importance of work times per shift and work shifts per day. These are the bases of planning in SLC.

C. *MODEL ASSESSMENT*

The model presented offers production planning for different periods in an underground mine. It can optimize the operation of a sublevel caving mine to maximize profit while considering various constraints. The goal function can use a profit discount factor instead of P^t, ultimately calculating the Net Present Value (NPV).

In this model, we cannot use other variables for the following reasons:

Let us assume that the variable in this planning model is the tonnage of ore extraction. Therefore, it is crucial to accurately determine the specific ore tonnage and volume in the surrounding region. If the extraction amounts from a stope are incorrect, it will lead to significant problems for the processing plant, which we must avoid at all costs. Even under these conditions, applying the ventilation constraint may be challenging.

The next stage involves treating the decision variable as a block that cannot solve problems or provide processing plant constraints in short-term planning. However, if a block is considered a small block with a volume of one cubic meter, one of the problems that leads to design challenges is the extraction of the blocks between stopes during the mining operation.

V. CONCLUSION

As open-pit mines reach a certain depth where economic extraction becomes unfeasible, mine designers and planners often transition to underground mining operations. This is a common situation for many mines, necessitating a shift to underground planning. In such cases, the cost-effectiveness of caving methods for extracting large ore bodies provides a reassuring solution. This study specifically focuses on the sublevel caving method, a cost-effective approach, and provides a production planning model tailored to it.

The main goal of the model is to maximize profit, and it incorporates standard constraints to achieve this objective. Additionally, the rock mechanics conditions of the hanging wall can influence the amount of waste extracted from each ring. Also, in this study, the ventilation constraint is defined to provide enough air volume for operation. This constraint can increase the safety of the operation, which is not considered in many studies.

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