In-Pit Crushing and Conveying Systems in Long-term Open Pit Mine Planning – Literature Review

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ABSTRACT

One of the transportation options in surface mining to reduce operating costs, especially in the deep open pit mines, is In-Pit Crushing and Conveying (IPCC). In this paper, broad research has been done over the literature on the long-term mine planning and the IPCC locations and relocations. Also, the possibility of integrated modeling of IPCC and long-term mine planning is investigated. The goal is to review and document the main optimization models considering IPCC's best locations and relocation times. The purpose is to understand the proposed academic solutions that could be hired to optimize the mining schedules and IPCC locations during a mine life and identify any gaps in the current literature so that one can define the opportunities to establish research questions for better optimization modeling of the IPCC and long-term open pit mine planning. It is evident that by locating the crusher inside the pit, lots of blocks are required to replaced. Elaboration on how to model these blocks in the constraints of a mathematical model is another aim of this review. Finally, the obstacles of current algorithms for general long-term planning or IPCC best locations problems, when explored separately, are documented in terms of mining practicality and optimality of the solution. The results of this literature review enable us to evaluate the logical links between significant components of an integrated optimization problem which could provide the best solution for both questions simultaneously.

1. Introduction

Surface mining is one of the most common methods compared to underground ones, and usually receives more attention from researchers. For example, we can take an orebody reserve with the equal score for selecting a mining method between underground and open pit options. Based on the Nicholas and UBC mining selection methods, an open pit extraction method is preferable to underground (Kuchta, M., Martin, R.K., & Hustrulid, 2013). It is mainly because an open pit mine is safer, more accessible in ore extraction, and has a higher production rate, bringing the money back much sooner. These factors make surface mining methods more desirable. In addition, original equipment manufacturers (OEMs) are providing equipment that tends to ease using surface mining methods. One effort to achieve this aim is providing the trucks with more capacities or equipping trucks with automated haulage system (AHS). These opportunities usually allow the mine designers to tackle the reservoir with a considerably low grade. As a result, the average and cut-off grade will decrease, and the stripping ratio will increase drastically. Increasing the stripping ratio means that a massive amount of waste must be extracted to reach one tonnage of ore. Mines will sustain longer, and their life and depth will increase more. However, by increasing the depth of

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the open pit, the distance between material destinations becomes more extended, which is not a desirable phenomenon, especially when the truck-shovel system (TS) is the most common and convenient way of transportation in the open pit mining. An extra cost of transportation accompanies the distance increment for trucks. Additional tire depreciation, fuel, and truck demand are some of the extra costs. These costs are divided into 1) capital costs, such as buying more trucks, and 2) operating costs, such as fuel and tires. One solution for overcoming these costs is designing In-Pit Crushing and Conveying (IPCC).

1.1. Motivation

The motivation for this paper is to review the latest knowledge in designing and scheduling the open pit extraction with IPCC. Usually, the mine designers do not consider the IPCC and its associated costs in the first steps of mine designs. By increasing the open pit's depth, trucks' operating cost suddenly turns into the mine's major problem. On the other hand, the whole mine scheduling must be changed since IPCC will change the mining and operating costs, and it needs a significant amount of capital investment. Planning is an impartible part of every open pit mining because mining operations must be optimized. Not considering this critical parameter, i.e., IPCC could jeopardize the mining operation's optimality and the mine's financial and operational targets' achievability. Investigating the reasons for this unwillingness is appealing and could reveal the advantages and disadvantages of such a decision.

1.2. Factors Contributing to Open Pit Mine Planning and Design

Many technical, geological, environmental, and economic factors must be addressed in open pit mine planning. IPCC can be mentioned mainly as a technical and financial factor. Nowadays, the size of mining operations is immense, so it is impossible to decide when exactly a specific block of ore or waste should be extracted and where it should be sent to be treated properly. The cost or profit is always involved in strategic and technical mine planning studies. The objective sometimes is to minimize the cost or maximize the profit within the specified time horizon. Mine planners are almost consensus that in the short-term, the cost must be minimized, and in the long-term, profit or Net Present Value (NPV) should be maximized (Mahdi & Morteza, 2014; Matamoros & Dimitrakopoulos, 2016; Osanloo & Rahmanpour, 2017; Blom, Pearce, & Stuckey, 2018). However, some improvised ideas are presented to minimize the capacity deviation by penalizing the extra costs while optimizing the long-term planning and keeping the NPV to a fixed constant level (Kumral, 2013). It is also known that the level of data uncertainty is higher in long-term planning compared to medium-term or short-term planning (Rahmanpour & Osanloo, 2014). In the short-term planning, however, most of the data are touchable and more reliable. Production targets set by long-term planning should be considered a goal of every short-term planning, which could be interpreted as the collaboration of long-term and short-term planning (Matamoros & Dimitrakopoulos, 2016). One of the main costs of every open pit mining is haulage, regardless of capital or operating cost. Tutton & Streck (2009) state that haulage costs in an open pit mine form 45% of the total operating costs and 40-50% of the total capital costs. Thus, IPCC is a crucial factor playing an essential role in mine planning despite the tendency of decision makers to evaluate and consider IPCC in the first step of the mine design or not.

1.3. Outline of the Paper

The rest of this paper is organized into the following five sections; in the first upcoming section, some of the features that a proper mine should have for implementing IPCC will be discussed in the background information. The necessity of using IPCC will be explained, and some past research will be presented in the second part. In the third section, the progress of the IPCC method will be covered. It mainly includes the issues solved using such a system and what makes this system attractive. Discussion about the main technological and commercial is covered in the fourth section of this paper. Also, the alternatives that the mining industry can hire in similar cases where IPCC has limitations will be investigated briefly. Three types of in-pit crushers are widely used in mining operations as the fixed, semi mobile and mobile in-pit crushers. The fifth section reviews the studies in which the three types of IPCCs are applied in long-term planning. Finally, the last section introduces two research directions as the leading subjects in optimizing the long-term scheduling in presence of IPCC.

2. Background Information

In-Pit Crushing and Conveying is a system in which the first step of crushing material is done in a specific location and elevation of the pit. The conveyor carries material from the crusher spot to the second crusher or mill plant located far outside the pit. This is one of the notable solutions for the distance problem that the TS system recently encountered. There are still some other solutions for the distance problem of the TS system, such as the ultra-class haul trucks, which need larger blasting size and loader capacity and lead to higher altitudes of benches. Applying a new technology like automated trucks or transferring from open pit to underground mining are two other solutions for distance problems.

2.1. Features of the Mine for Using IPCC

There are some features one mine should have to be proper for implementing the IPCC. Additionally, IPCC has different models, each of which is appropriate for specific surface mining methods. However, uncertainty is a prevailing phenomenon governing the whole mining operation. Due to the lack of data, particularly in the first stages of mine design, the mine reserve might be estimated with errors. Despite being large or small, which is a key factor in deciding whether IPCC is suitable or not, the uncertainty within the parameters needs to be measured. Three types of uncertain sources in the mining industry are economic, technical, and geological uncertainties (Meagher et al., 2014). However, there is not any trace of investigating the IPCC option under these uncertainties in any research on this subject.

There are three types of IPCC, according to Utley (2011), which have their specifications and usage limitations: fully mobile crusher, semi-mobile/ semi-fixed crusher, and fixed crusher. Fully mobile crushers are usually used in horizontally advanced surface mining like surface coal or open cast mining. Using fully mobile crushers could significantly reduce or even eliminate the truck requirement that reduces the operating costs drastically. Semi-mobile/ semi-fixed are two types of crushers with many similarities, so they have been taken together. The only difference is the time of relocation, which occurs by deepening the pit. They need to be inside the pit within the benches, and trucks to be available beside the loader or shovel for carrying the material from working faces to the crusher. The relocation time for this type of crusher varies between 1 to 10 years. Fixed crushers usually stay inside the pit in a specific location for at least 15 years (Osanloo & Paricheh, 2019a). This type of crusher is like the semi-mobile/semi-fixed crusher, but its cost of relocation is considerably lower.

Koehler (2003) mentioned three specifications that a mine needs to be capable of for IPCCs to be practicable as: 1) long project life, 2) lengthy transportation system, and 3) high production rate. When the mines become more extensive, a series of problems start, and the consequence is an increment in operating costs. In a deep pit, the truck cycle time may increase, resulting in requests for ore trucks. Dispatching could become a big issue with a large fleet of trucks, so more labor and supervision should control the haulage process. Maintenance and repairs are other irritating factors that would increase the number of trucks. Diesel fuel is used as an energy resource for trucks, which is the main reason for operating costs and environmental pollution. Using IPCC will reduce fuel consumption by up to 60 million liters per annum (MLA) as happened in a Brazilian iron ore mine with two fully-mobile IPCC and a combined capacity of 800 t/h (Raaz & Mentges, 2011).

Based on McCarthy (2011) and Turnbull (2011), the fundamental keys for the IPCC nominated mines are as follows.

1- For IPCC to be cost-effective from the capital cost point of view, the production rate of the mine must be greater than 4 Mtpa, but 10 Mtpa is more desirable.

2- Making the operating costs lower so that the payback period of IPCC becomes shorter. It usually happens when the mine life is more than ten years. Since most of the IPCC's installed in the middle or last years of mine life, it is recommended that the remaining mine life will not be less than ten years.

3- Electricity costs ($/kWh) should be less than diesel fuel costs ($/t) for IPCC to be favorable. This range should be greater than or equal to 25%.

2.2. Necessity of Using IPCC

There are several research studies about the possibility of installing IPCC as an option for cost reduction (Koehler, 2003; Szalanski, 2010; Ribeiro, Sousa, & Luz, 2016; Dzakpata, Knights, Kizil, Nehring, & Aminossadati, 2016; Abbaspour, Drebenstedt, & Dindarloo, 2018). These all show that the cost, which is increased by the depth increment, grade decrement, and commodity price variability is a serious concern among mine managers. Implementing the IPPC has been reported even among those mines which already passed the depth of 1000 meters and might even have switched to the underground at this time (Osanloo & Paricheh, 2019a). Some examples of these mines are Bingham Canyon, Morenzi, and Chuquicamata, where semi-mobile/ semi-fixed systems were used in the 1980s. Chuquicamata has used this system for ore and waste transportation, and Bingham Canyon used this system just for ore transportation (Kammerer, 1988; Tutton & Streck, 2009). Investigating the options of hauling waste with IPCC has always been a subject of serious discussion because of its disadvantages.

Based on the data gathered from IPCC manufacturers by Ritter (2016), From 1956 onward, 447 IPCC system have been installed throughout the world, with Europe having the maximum number of installations (147) and the Middle East having the minimum installation (16). Since then, the application of in-pit crushing and conveying systems has been increasing in the mining industry. Additionally, the capacity of IPCCs is increasing from 100 - 500 (t/h) in the early use of this technology to 10,000 - 14,000 (t/h) recently. The three most common uses of such a technology are limestone, coal, and iron ore. There is also a significant number of installations of this system for waste material transportation rather than ore. This could be because of the single destination of waste material has, and there is no need to separate it for different destinations. Historical data shows that most European IPCCs have fully mobile capacities of less than 2000 (t/h).

2.3. Past Research

In 1956, the first IPCC system was introduced in Werk Hover mine, Germany (R. Ritter, A. Herzog, 2014). Many researchers tried to address the efficient use of IPCC from that time onwards. Lonergan & Barua (1985) investigated slope reduction costs to minimize the haulage cost by minimizing the conveyor slope. Dos Santos & Stanisic (1986) reintroduced and explored the option of hiring high slope conveyors. Sturgul (1987) and Rahmanpour et al. (2014) tried to find the best location for an in-pit crusher. Another solution that Roumpos et al. (2014) mentioned is finding the best place of distribution point for belt conveyors.

Nowadays, mine designers are more concerned about the semi-mobile/ semi-fixed model of IPCC because it has more flexibility to work with TS systems. Therefore, most of the studies are related to the subject of installing and relocating the semi-mobile/ semi-fixed crusher in a proper time and transferring it to the most appropriate location. This problem is solved through mathematical modeling concerning optimizing the crusher's location and time of relocation. A simplifying assumption is an integral part of any optimization problem, mainly because of the complexity of most technical problems. For instance, in this optimization problem, the relocation places are some fixed points in the centroid of the working faces, but they can vary in height. On the other hand, the optimum time problem is limited to the end of each production year, but assembling and disassembling time are not considered.

Abbaspour et al. (2018) provided a Simple transportation model to solve an optimum location and time problem. They claimed that this model enables them to search for the optimum time and location simultaneously. Using this model, they solved a 2D hypothetical mining section. Paricheh et al. (2017) modeled the IPCC location problem with the linear programming method as a dynamic problem. The authors calculated the haulage cost with two functions, one for truck systems and the other one for conveyor systems. These two functions evaluated the haulage cost based on the annual mining elevation. Therefore, the location and time of relocation can be provided. With those two cost functions and mathematical models which can determine the optimal location, Paricheh et al. (2018) presented a heuristic approach to find the optimum time and location. In the proposed heuristic, the data model has two objective functions: the first one to minimize costs and the second one to maximize the NPV. Because the variables for these two models were not the same,the maximization of NPV needs a nonlinear function and hence the model is solved with a heuristic approach. Based on this model, when the haulage system is changed, the cost of the transportation method will be updated and the block value must be recalculated with a new cost. Using IPCC will reduce the costs, which should enlarge the pit size. This model has to run for several iterations to access each defined step, like finding the transportation costs for each period, determining the best location and the best time, and then reaching the new ultimate pit limit. Nehring et al. (2018) offered a strategic mine planning comparison between IPCC and TS systems. According to the authors, *"A completely different approach to planning and design must be followed. This is principally due to the unique shape and sequencing constraints associated with introducing conveyors into the pit for haulage purposes."* Relying on this thought, they came up with a number of hypothetical 2D sections of the block model. Searching among the various options through the possible sequence of extraction may result in catching a higher NPV and cash flow. The most beneficial point about investigating the possibilities for finding the optimum sequence of extraction is that once the operation is set, it cannot be changed easily in the IPCC system. Therefore, doing so helps to measure the feasible consequences of every option.

The only research which claimed that it considered uncertainty in parameters for the optimum in-pit crusher's location is an article by Paricheh & Osanloo (2016). Different production scenarios were added to the mathematical modeling to minimize transportation costs. For this purpose, three equal possible states with a 10% increase or decrease for each parameter are assumed, in which every one of the three possible productions has a costs scenario. These scenarios can remain either fixed, decreased, or increased. Taking the haulage cost into consideration may yield the optimum solution.

3. The Progress of the IPCC System

This section discusses some of the progress since this system's early application. Now, the installed location for this system is constrained to limestone mines, coal mines, and some of the large mining operations with iron ore or copper. This system seems to have a long way to progress and adapt to the mining industry since it is in the middle of this path. We can still talk about the TS system for at least tens of years as the most dominant transportation system in open pit mining.

3.1. What types of IPCC problem have been solved?

One of the most common problems for the IPCC application is the optimum location and time of IPCC installation. Almost all of the literature that applied mathematical modeling for this optimization problem has been reviewed in the previous section. Still, several key factors have to be taken care of. Regarding facility location problems, there are two types: static and dynamic. When the parameters are fixed within the scheduling time, such a problem is "static facility location". In contrast, "dynamic facility location" is when the parameters change through the time of the mine planning.

The main factors which may affect optimum location and relocation are as follows.

1. Haulage distance and truck operating costs
2. Mine schedule and block sequences
3. Rate of increase in haulage costs with increasing in haulage distance and time
4. Conveyor operating costs
5. Additional haulage costs, which may divide into vertically depth increment and energy loss
6. Cost of relocating the system, which may categorize as: engineering, disassembling, installation, labourer, transportation, overhead costs and cost of purchasing an additional conveyor (Paricheh et al., 2017).

Some of the factors mentioned above are not considered, or are considered but solved for the hypothetical sections in the research studies, like the mine scheduling and sequencing of the blocks, which is mentioned by Nehring et al. (2018) but for a hypothetical section without modeling it mathematically. Some others are calculated for a specified case which cannot be extended for the other cases, like rate of increase in haulage costs with increasing in haulage distance, time, and additional haulage costs in the works of Paricheh & Osanloo, (2016), Paricheh et al., (2017) and

Paricheh et al., (2018). Another flaw in the rough cost estimation exists in Paricheh et al. (2017), which is worth noting.

Capital cost requirements, and the laborers and engineers' unfamiliarity with the new system will be discussed as two of the main limitations of the IPCC system later in the next section. Flexibility and selectivity problems are addressed mainly by Paricheh & Osanloo (2016) and Nehring et al. (2018). Both of these papers try to solve the flexibility before installing the system. However, the problem with the idea of studying various options is that it often ignores most of the other occurrences that might be the case, so it cannot be generalized. For example, if the commodity price increases suddenly, we will try to utilize this opportunity by increasing the production rate. Although such a circumstance is predictable, it can not be well-treated through the option investigation methods. The capacity of IPCC is fixed, so using IPCC with excessive capacity imposes financial loads on the mining managers, which will be rejected undoubtedly. Another example of a bizarre event is slope failure which could cause an unprecedented problem according to the size of the incident.

3.2. What makes this system more attractive?

As mentioned earlier, except for the IPCC system, there are three other alternatives proposed by the researchers that are tested or used by the mining industries throughout the world to overcome the increasing stream of operating costs. These three alternatives are ultra-class trucks, automated driverless trucks, and underground transition.

The ultra-class trucks need more space for the haulage road, which increases the incident possibility. The blasting operation must be extensive enough to feed these types of trucks properly so that mining recovery will decrease, and dilution will increase. This will result in higher costs in the processing plant and less recovery. They also create a dispatching problem since the fleet size becomes much disparate. The transition from open pit to underground also needs considerable capital investment and preparation in tunneling and well-drilling, which takes time and money. Automated driverless off-highway trucks are another option used in Western Australia (the Nammuldi and Yandicoogina iron ore mines. They can only compensate for the driver costs, which is 20-30% of the haulage cost. These trucks require a high investment and proper hardware and software with a price of up to 20 M$ (Bellamy & Pravica, 2011).

Flexibility and selectivity, plus mine engineers' and laborers' tendency, are among the most important factors hindering the widespread usage of the IPCC system (Morrison, 2017). The target of each mine for each year determines by the expected revenue. However, the price sometimes falls in a way that special planning may be needed. In addition, the TS system has been used for decades in open pit mining. The technicians cannot easily incorporate in-pit crushing and conveying into the mine planning. Almost none of the mine planning software have an IPCC option, so this is where researchers must interfere to facilitate the application of such a system for the industry.

4. Main Limitations of the IPCC

Although, the IPCC system has been designed in a way to settle into most of the TS systems, still big limitations remain. Some of these limitations are capital investment mine designer's unfamiliarity and labor intensiveness. In addition to those fundamental limitations, there is a shortage in the related research topics to make the subject clearer for the mine planners and designers. Here in this section, the financial and technical limitations will be mentioned and then the existing mathematical models will be criticized.

4.1. Financial limitations

The amount of money that a mine requires to install an in-pit crushing and conveying system is 180 – 250 million dollars (Foley, 2012). This cost will be desirably decreased to almost 5 million dollars for buying a 360-ton truck (Czaplicki, 2008). The story starts with the huge capital costs of the IPCC, but it has some remarks. Increasing the haulage distance will necessitate more tier, fuel, road maintenance, parking lot, water wagon, dozers, front-end loaders, and cranes. These factors, plus having 3 to 4 times more trucking per kilometer than the conveyor's cost, lead to more operating costs for the TS system. However, the TS system has more flexibility in the case of multiple destinations (Osanloo & Paricheh, 2019a). Moreover, by using a semi-fixed/ semi-mobile crusher, the need for a TS system will not be completely eliminated. Every mine has at least two destinations: one for the mill plant and one for the waste dump, apart from the fact that most mines have more than two destinations. A separate installation of the IPCC system can be considered for each destination. Likewise, crushing the waste sometimes, as in waste stripping, would not be necessary most of the time, and implementing IPCC would be a waste of time and energy. Hence, by using the IPCC system, some trucks must still go down deep and return to the surface.

A good number of papers evaluate the IPCC option for ore or waste. The IPCC implementation could be approved using a feasibility study for the mines that are big enough (i.e., more than ten years of operation or having a long haulage road). Although Dilhuydy et al. (2017) and Dixon (2015) proved that for a big mine like Highland Valley Copper, the IPCC installation option for the waste material is still worth the price, such a decision is controversial mainly because sizing the waste through crushing would not be rational.

Using mobile crushers will eliminate the haul truck usage, at least for the ore part. On the other hand, using fixed crushers or semi-mobile/semi-fixed crushers will not entirely eliminate haul trucks in the open pit mines, but it will drastically decrease the required truck number. For example, in an iron ore deposit investigated by Marco de Werk et al. (2017), conducting semi-mobile/semi-fixed IPCC for the ore will decrease the number of haul trucks with 144 capacities to 2, where it was required 6 of them without conducting the IPCC.

4.2. Technical Limitations

Due to the lack of flexibility in the in-pit crushers, there is a strong disinclination toward this system. Applying IPCC in the middle of the mine life must be done after the first payback period (Paricheh et al., 2017). After the first payback period, there are two options on the desk: going for the new truck fleet (if needed) or installing the IPCC. However, the easiest option is to use the existing truck fleet and do the required modifications. That is why most mines will not use IPCC after the first payback period. When a mine gets deep adequately, the necessity of using this system will make more sense. This is when most of the laborers and truck operators should either change their workspace or be fired from the company. It is a case of major conflict that directly influences mine's productivity.

There are a few but major problems, which is accompanied by conducting an IPCC in the open pit mines. For example, for moving the movable IPCCs from one bench to a lower bench, the road width must be wide enough since the crusher's dimensions and the crawler carrying it is different from the regular haul truck's dimension (Konak et al., 2007). As a result, the geometry of the pit and the appropriate required access must be further created. Another problem is the labor's unfamiliarity with the system and unprecedented incidents such as conveyor damages by blasting operation, which make this system cause a considerable loss of time. Due to this unfamiliarity and unprecedented incidents, the maintenance time will take longer than predicted, or the conveyor moving or repairing time might need more labor than calculated. The loss of time could be why most IPCCs cannot provide the return on the investment in the promised period (Morrison, 2016).

4.3. Mathematical models limitations

There are a few studies about the optimum location and optimum time of relocation. The simplest one which models this problem within the transportation problem is presented by Abbaspour et al. (2018). The general idea of this model is to find the amount of material that must be sent to a specific level ($x_{i,j}$), resulting in a minimum amount of total operating and relocating cost ($c_{i,j}$). The mathematical formulation of the problem is as shown in Equations (1-5).

$$minimize\ Z = \sum_{i=1}^{m}\sum_{j=1}^{n} C_{ij}x_{ij} \quad (1)$$

$$x_{i1} + x_{i2} + x_{i3} + \ldots + x_{in} = a_i \ \ (i = 1, 2, 3, \ldots, m) \quad (2)$$

$$x_{1j} + x_{2j} + x_{3j} + \ldots + x_{mj} = b_i \ \ (j = 1, 2, 3, \ldots, n) \quad (3)$$

$$\sum_{i=1}^{m} a_i = \sum_{j=1}^{n} b_j \quad (4)$$

$$x_{ij} \geq 0 \quad (5)$$

Equation (1) is the model's objective function and minimizes the total haulage cost. Equation (2) indicates that all sources' total availability is equal to *ai*. Similarly, Equation (3) indicates that the total demand at all destinations equals *bj*. Additionally, Equation (4) guarantees that total availability and demand must be equal. Finally, Equation 5 sets the non-negativity condition of the variables.

As it was mentioned earlier, since IPCC changes the total costs of transportation, the value of each block model should be updated, which may cause changes in the ultimate pit limit and the whole mine planning. So, any mathematical modeling for optimization of IPCC must keep the mine planning optimum. Otherwise, the idea of adding a new system into the optimum system to reduce the costs of keeping the system optimum would not be rational. This model's first drawback is its inability to check the mine planning optimality. The second impediment of this model is that there is a possibility of sending the entire production in one year to only one level or a different level other than the destination level. Finally, this model has been tested for the hypothetical 2D section of a copper deposit, which might have a bad result since the case sensitivity of the problem has not been investigated.

The second mathematical modeling effort is a series of the dependent models presented by Paricheh (2016), (2017), and (2018). These models are developed one after another to the point that they can return the optimum pit while optimizing the IPCC's location and time of relocation. They require two functions for cost calculation estimated for the case study and cannot be used as a general formula. In the first step, they simply optimize the location of the crusher by integer programming and assuming some predefined locations in which the transportation cost of each location for both IPCC and TS systems is known. Since the depth of mine is the function of time and production rate, searching different times enables them to find the best relocation time (Paricheh et al., 2017). This search can also be done using different production rates (Paricheh & Osanloo, 2016). The third study starts with the integer programming for optimization of the crusher location, and in the next step, it estimates the NPV. This model is processed through the heuristic approach using a particular procedure and series of iterations (Paricheh et al., 2018). The mathematical form of the problem is as shown in Equations (6-17).

Objective Function:

$$z = \sum_{k=1}^{r}\sum_{j=1}^{p}\sum_{i=1}^{m_k+1} F_{kij}x_{kij} + \sum_{k=2}^{r} C_k y_k \tag{6}$$

Subject to:

$$y_k = 0.5\sum_{j=1}^{P} w_{kj} \forall k \tag{7}$$

$$w_{kj} \geq z_{kj} - z_{(k-1)j} \ \forall j, k \tag{8}$$

$$w_{kj} \geq z_{(k-1)j} - z_{kj} \ \forall j, k \tag{9}$$

$$\sum_{j=1}^{P} z_{kj} = P \ \forall k \tag{10}$$

$$\sum_{j=1}^{P} x_{kij} = 1 \ \forall i, k \tag{11}$$

$$x_{kij} - z_{kj} \leq 0 \ \forall \ i, j, k \tag{12}$$

$$z_{kj} = \{1, 0\} \ \forall j, k \tag{13}$$

$$x_{kij} = \{1, 0\} \ \forall \ i, j, k \tag{14}$$

$$y_k = \{1, 0\} \ \forall \ k \tag{15}$$

$$Z = \sum_{k=1}^{t} \frac{CF_{truck}}{(1+d)^k} + \sum_{k=t}^{r} \frac{CF_{IPCC}}{(1+d)^k} \tag{16}$$

$$b \leq t \leq r \tag{17}$$

Where r is the number of periods, p is the number of candidate locations, m_k is the number of faces in period k, and F_{kij} is the total haulage cost from face i to candidate point j in period k. In order to consider the operating and capital costs of the conveyor from candidate point j to the mill in period k, the value one is added to m_k on the third summation. C_k is the relocation cost, including engineering, disassembling, installation, labor, transportation, and overhead costs. x_{kij}, z_{kj} and y_k are binary decision variables. CF_{truck} and CF_{IPCC} represent the cash flow of pure truck and IPCC systems, respectively. The variable t is the upper bound of the first summation, meaning that the pure truck system will be used up to the year t. Also, it is the lower bound of the second summation because the IPCC system will be used from the year t to the end of the mine life. d is the discounted rate and k is the periods' index, $k = 1, 2, \ldots, r$.

This model improves NPV by 1% and cash flow by 150 million dollars based on the results being extracted from the case study. The author states that the solution will improve closer to the optimum point by performing the procedure for more than one iteration. However, the reason why it is not being run for more than one iteration for the case study is not explained. This model is non-linear, and the procedure is heuristic which does not guarantee the optimal answer. Since the NPV changes the transportation system, it is not appropriate to calculate the time of starting IPCC beyond the scope of mathematical modeling. The reason is that there is a possibility that increasing the production rate and reaching the specific depth will accelerate the installation of the crusher, which improves the NPV more as a consequenc.

5. Long-term production planning and IPCC

IPCC is a complex transformer that needs a good number of blocks extracted before and after installation. That is why the mines with IPCC must have a long-term production plan considering IPCC in the planning. Additionally, IPCC requires relocation to reduce the transportation time and facility so that the extraction sequence will be disturbed from the usual long-term planning.

It has been discussed earlier that the IPCCs are being divided into three categories, each having its particular characterization and application. Undoubtedly, providing an optimized mine plan for each category will differ mainly by the necessary constraints and the required precedence. The TS-related cost must be replaced by the operating cost of applying, relocating, and maintaining IPCC in the mining cost calculation section of the block economic value estimation.

The first step towards any planning for the mine with the IPCC is to decide where to install such a system in the mine and what would be the possible places for the IPCC. Paricheh & Osanloo (2019) provided a new search algorithm aiming to do so. The authors divided the whole pit into some areas which have the same pushback among some benches, and then based on the azimuth of these areas, the location of the IPCC will be confined within the several hundreds of points as the candidate locations named as a Phase-Bench-Slice (PBS)

Afterward, some of the candidate areas removed with the below-mentioned specifications.:

I. Depth: Minimum depth with the maximum haulage distance – they assumed that the IPCC would not be installed above this altitude.

II. Pushback: for a mine to be applicable for IPCC installation, it is necessary to pass the first payback period so the IPCC location cannot be within the first pushback.

III. Required space for installation: some of the PBSs are not big enough for an IPCC to be installed.

IV. Radius of influence: IPCC will stay in each candidate location for a while after installation and will not relocate before one year. On the other hand, the progress of the mine could be more than one or two benches within a year. So those locations will be eliminated.

V. Value restriction: best candidates have the zero-value underneath them or at least the minimum value.

5.1. Long-term planning with fixed crushers

The time of installing a crusher inside the mine, its capacity, and its location are among the decisions that must be made for fixed crushers. Londoño et al. (2013) has modeled the alternatives of In-Pit Crusher and Conveyor. In this paper, a coal mine is modeled to engage the IPCC with a dragline and hopper for coal digging. The authors use simulation with "3D-Dig" package software to analyze three options for the IPCC location, and the inside of the pit option is determined as the most cost-effective one. Additionally, they searched through the application of a parallel conveyor and spreader through simulating it for one hundred replications and comparing it with a single conveyor and spreader. It is concluded that the parallel conveyor and spreader can increase the availability by more than 9 percent, although the cost of a single conveyor is indeed lower than the parallel one.

Roumpos et al. (2014) provides an optimal location among the various nominated points for the belt conveyor system in a continuous surface mining operation. This paper is mostly about finding the location of the conveyor belt in an actual lignite deposit that is expanded horizontally in four benches. The authors proposed a method to find the conveyor belt location by searching through the perimeter of the pit level by level and giving the location with the minimum cost. The cost formulation is presented based on the distance of the conveyor and its energy consumption. The study is more of a search algorithm with a heuristic approach within the limited number of nominees for a conveyor belt.

5.2. Long-term planning with semi mobile/semi fixed crusher

For these crushers, all of the previously mentioned parameters for the fixed IPCC plus two other parameters must be estimated. Thus, the decisions are to be made about the time of installation, capacity and location, plus the time and the new location. The subsidiary parameters are the conveyor's location, the pit's geometry, and the conveyor's angle. Knowing the mentioned considerations, determining the location of the IPCC is categorized as a long-term planning parameter. Finding the best locations for the IPCC is searched through a simplified method by Konak et al. (2007) for crashing gravels in a limestone mine in Turkey. In their research, the best location for the crusher is decided based on the number of nominated locations, selected mainly by dividing the mine area into various segments. The idea behind this research is to find a location with the minimum haulage cost, which starts from the stationary crusher and goes all the way to change the location of the crusher for the first, second, and finally a third time. However, this study does not consider the cost of relocation, nor it provides the appropriate optimization process in which the structure dictates a confined objective function. Thus, the haulage cost minimization process between thousands of nominees is to be done for three relocations. It is proven that the haulage cost is decreased by increasing the number of relocations. The most important result of this study is that the number of relocations must be well calculated and strongly determined before the operation, which cannot be decided in the middle of the mining operations. The reason is that the optimum locations of the crusher for two relocations are simply different from the same situation with three or more relocations. Therefore, haulage cost will not remain minimum if one decides to add or deduct another relocation in the middle of the mining operations without preplanning, resulting in a robust model.

Yarmuch et al. (2017) is another study that tried to find the best location for adding one crusher in the Chuquicamata mine. This mine is one of the deepest mines in the world, which already has two crushers; one is located inside the pit, and the other one outside the pit. The authors try to search for the best possible location for adding another crusher so that this newly added one could compensate for the possible operational failures that two other crushers might have. The candidate locations are beside two existing crushers. The authors formulated these two options based on the probability of operational failures of the crushers and their conveyor belt. The Markov chain is used to simulate their problem with the probability and costs of the failure and the installation costs. This problem is solved for four years with an 8 percent discount rate in the cost calculations.

One of the related studies about finding the IPCC location, which was done using short-term planning parameters such as operating costs, is done by Paricheh and Osanloo (2016). The authors first introduced two common approaches for facility location's uncertainty as the probabilistic and robust (scenario-based). In the latter approach, three models can be hired or incorporating scenarios into the model:

1- Expected performance optimization within all scenarios,

2- Worst case performance optimization, and

3- Expected loss or regret minimization within all scenarios.

The developed model is based on the third concept for the 10th year of mine life if the mine needs two IPCCs, and they optimized the location of these two IPCCs for the year 10 with GAMS. The authors also proposed a cost equation that gives the haulage cost in different periods of the mine life. The facility location problem, solved in their paper, is designed for two or more facilities; otherwise, the model's scope will turn into a deterministic problem.

In another study, Paricheh and Osanloo (2017) tried to minimize the costs throughout the proposed model and at the same time, they optimized the model for 22 years (from year 6 to 27 of the mine life). Two cost estimations formulations are created by them in which there is no relocation cost, so they provided an estimate solution for that.

So far, there is not any mathematical optimization introduced or proposed so that it could optimize the IPCC location and relocation time while optimizing the long-term planning of the mine. In another work Paricheh and Osanloo (2020) tried to optimize the production schedule in presence of the IPCC through a MILP model concurrently. There are a few assumptions that authors have considered for their MILP model.

a) The UPL is pre-calculated based on the known average haulage costs.

b) The costs and prices are all constant during the mine life.

c) The truck fleet has the same size as all the fleet.

d) In-pit and ex-pit crushers have the same costs.

e) There is a separate conveyor for each crusher

The objective is to optimize the schedule by maximizing the NPV and, simultaneously, find the location and time of relocation of the ex/in-pit crushers and optimize their capacities.

The author compared the original proposed MILP model with two simple benchmark MILP models, one of which is scheduling while optimizing the fleet size and the other one just scheduling the blocks assuming the predefined fleet size. The authors solved these three models for two hypothetical copper block models over 15 years. All the three models are solved in CPLEX. The run time for the first model was around two hours, and around a few seconds for the other model. This model, however, is solved for a limited number of blocks and does not represent a complete mine, so it cannot be considered as a practical model.

5.3. Long-term planning with mobile crusher

The capacity is still vital for this type of crusher; however, the crusher's location is no longer a field of discussion as it moves alongside the loader. On the contrary, the conveyors' location is important, so a series of precedence must be defined.

One of the most recent works towards mine planning and production scheduling for the mobile crusher is the study of Samavati et al. (2020). That divided the conveyors into three types, as the main conveyor, the transfer conveyor, and bench conveyor. Between these three, the transfer conveyor is fixed within the level, and the bench conveyor moves alongside it. The main conveyor that transfers all the material from each bench to the outside of the pit is usually inclined, and its longitude increases towards the pit's depth. They have developed a MILP model for the problem, with a set of constraints controlling the precedence among the blocks to make sure that the conveyor's location will not be extracted.

The authors solved the model for the hypothetical block model through three different heuristic approaches plus the MILP, and then compared the answers, showing that the M3 heuristic approach is faster and more precise. The biggest block model they could solve 40,000 blocks which could barely account for a medium mine, meaning that the proposed model cannot be used in real mines. Additionally, the number of precedences they considered makes a significant number of constraints roughly equal to the number of blocks multiplied by 16, making the problem so complicated to solve using exact solution methods.

6. Future Research Direction

The future direction of the long-term mine planning with the in-pit crusher can be introduced into three following topics; The first proposes a cyclic procedure to start from the pit and end with the crusher-related optimization. Since the process of optimizing a mine schedule is a cyclic process, a small change might burden starting the process from scratch. Bringing the crusher inside the pit, installing the conveyor, changing the slopes for conveyor placement, and preparing the related ramps and roads to the crusher are some significant changes that make the workload of starting over more appealing. As for the second direction, the necessity of optimizing in-pit crusher and mine scheduling is overexplained here in this paper and other related papers (Osanloo & Paricheh, 2019b; Morteza Paricheh & Osanloo, 2020a; Samavati et al., 2020). The third research direction refers to the uncertainty of the IPCC models, which is generally rare in ideas and applications due to the lack of information on the technical and operational aspects of the area.

6.1. An effort to optimize a pit to crusher operation

Liu & Kozan (2012) provided an interactive planning and scheduling framework for optimising pits-to-crushers operations. This study, after reviewing mine design papers, mine production sequencing papers and mine transportation scheduling papers, provides a model based on the job sequencing for the minimization of the costs throughout the mine life. This model takes the ultimate pit limit from a MILP method and tries to make a block sequencing using an assigned timeline for each job. In this model, the so-called jobs are transporting material from multiple sources to multiple destinations. The timelines consist of ready times, starting times, completion times, flow times and tardiness times which, according to the authors, there has not been any research about the influence of a time in a job sequencing. However, the authors did not implement their proposed model in any real case study.

6.2. Simultaneous optimization

The process of optimizing the crusher locations and relocation times is often taken separately from the mine planning; however, it affects the extraction sequence so as the block destinations and requires a new set of precedences. As yet, two papers propose models for optimizing the crusher and mine planning simultaneously (Paricheh & Osanloo, 2020b; Samavati et al., 2020). The first one is for the semi-mobile crusher, which is solved for a hypothetical 2D block model with a heuristic approach. The second one is for the fully-mobile crusher, which provides a solution for a relatively medium mine size. Both proposed methods are within the block level, making them inefficient to take the real mine operation. Additionally, both methodologies are robust with many precedences and ignore the road network of the mine, so a new type of methodology is required.

6.3. Uncertainty based models

The uncertainty-based models usually give a better perception to the researchers of the areas which should move cautiously. Generally, a sensitivity analysis is required to find the delicate parameters and change them appropriately. Nevertheless, in the area of in-pit crushing and conveying, the ambiguity of the parameters' effectiveness has not been studied yet. Although in the literature, one study takes different options for production and operating cost by creating varios production deviations from the production target to determine the optimum locations (M Paricheh & Osanloo, 2016). The missing portions are the stochastic programming models, which could give a better horizon of the technical or financial parameters in the IPCC and mine planning optimization.

7. References

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