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Optimum location and relocation plan of semi mobile in-pit crushing and conveying (SMIPCC) systems in open pit mines by transportation problem

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Abstract. In-Pit Crushing and Conveying (IPCC) systems are known as a transportation system in mines, which are considered as an alternative for the conventional truck-shovel system. Among different types of IPCCs, Semi Mobile In-Pit Crushing and Conveying (SMIPCC) system is in a high interest in mining projects because of its relocation feature. However, it is very important to design its optimum location and relocation plan in a manner that minimize the operating costs. In spite of some previous works, which propose methods for this problem, they are not able to evaluate both location and time of relocation at the same time. This paper defines the optimum location and relocation plan of the SMIPCC in a frame of a transportation problem with different "sub-phases" as the sources and "benches" as the destinations. This model is able to calculate the optimum solution simultaneously in the both case of location (bench) and time (sub-phase). The results show that this method can efficiently use as a planning tool for calculating the operating costs, optimum location and relocation plan of the SMIPCC.

Key words: semi mobile in-pit crushing and conveying (SMIPCC) system, transportation problem, optimum location and relocation plan, operating costs.

1. Introduction

Truck-shovel systems, which are known as the conventional transportation systems in mines, are widely used in mining projects. In spite of benefiting from some positive features especially their flexibility in operation, they suffer from some negative points such as high operating cost. These costs approximately constitute 50% to 60% of the total operating costs of a mine [1]. This issue will be more challenging when an open pit mine becomes deeper. In this situation and because

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of increasing the haulage distance, more trucks need to be operated in order to fulfil the plan of the mine's production. As a result, not only more trucks must be purchased, which force extra capital costs, but also higher operating costs will be imposed to the project. In addition, in some cases, it would be necessary to repair or replace the trucks, shovels or mining equipment during the project [2,3]. These drawbacks are not limited in economic issues but also can be found in the environmental and safety issues [4]. Emissions from trucks and accidents are the most common environmental and safety concerns about trucks [5,6,7].

In-Pit Crushing and Conveying (IPCC) systems, which were used for the first time in Germany [8], were introduced as an alternative for the conventional transportation system in mines [9]. It generally resolves many deficits of truck-shovel system e.g. reducing operating costs [10] mainly because of the reduction of the labour force and fuel consumption [11]. Moreover, this system provides a continuous transportation system in transferring ore to the destinations, which mostly results to a higher rate of production. Despite of these advantages, there is still some particular attitudes to its flexibility [12], reliability and efficiency [13].

Generally, this system is categorized into four different types: 1) Fixed In-Pit Crushing and Conveying (FIPCC) systems, in which the location of the crusher is fixed along the mine's life. Commonly, the position of this type of IPCC systems is near the pit rim or inside, which is not affected by mining operations. 2) Semi-Fixed In-Pit Crushing and Conveying (SFIPCC) systems, which do not benefit from an integrated transportation system. This type is located in a strategic junction point in the pit and mostly is fed by the mining trucks. Its relocation needs disassembly of the entire crusher station into several parts or multiple modules. 3) Semi Mobile In-Pit Crushing and Conveying (SMIPCC) systems, which do not have an integrated transportation system and commonly located at the operational level. It is possible to be fed through trucks or loaders from different loading points. 4) Fully Mobile In-Pit Crushing and Conveying (FMIPCC) systems, which can continuously change their location and benefit from an integrated transportation mechanism [14].

Optimum location and relocation plan, which plays an important role in the mine planning, is one of the most important issues regarding to these systems. In spite of the fixed and semi fixed in-pit crushing and conveying system, semi mobile in-pit crushing needs to be periodically relocated based on the scheduling process of the mine. This relocation plan could be between 6 to 18 months [15]. Additionally, there are some estimations about the relocation time of different parts of the system and starting it up again [15]. Many researchers tried to determine the optimum location of the semi-mobile in-pit crushing systems. Rahmanpour et al. [16] introduced the location problem of the semi mobile in-pit crushing systems as a single hub location problem in order to minimize the haulage cost and environmental effects. However, they did not consider the optimum time for relocation of this system. Paricheh & Osanloo [17] investigated about the optimum location of in-pit crushing and conveying system under uncertainties specially the production and operating costs through the stochastic facility location model.

Paricheh et al. [18] proposed a heuristic method to determine the both optimum location and relocation time of in-pit crushing and conveying systems. However, this model evaluates the optimization process in two different steps (optimum time and optimum location) through minimizing the haulage costs.
Up to now, any effort regarding the location and relocation time of the SMIPCC system, only covers a part of this problem. Accordingly, this paper is going to define simultaneously the optimum location and relocation time of the semi mobile in-pit crushing and conveying system as an integrated problem. This purpose will be achieved through defining a transportation problem, which will be described in the following sections.

2. Transportation problem

Simply description, transportation problem deals with the transportation of commodity from different "sources" to different "destinations". This problem is dealing with finding the minimum cost of transporting a commodity from these sources to a given number of destinations.

2.1. Mathematical Formulation

Suppose there are m sources $S_1, S_2, \ldots, S_m$ and n destinations $D_1, D_2, \ldots, D_n$. Let consider c_{ij} as the cost of transporting one unit of commodity from S_i to D_j and x_{ij} as the quantity to be transported from S_i to D_j. Then the problem is:

$$Minimize\ Z = \sum_{i=1}^{m}\sum_{j=1}^{n} c_{ij}x_{ij} \tag{1}$$

The total availability at the source S_i is a_i i.e:

$$x_{i1} + x_{i2} + x_{i3} + \cdots + x_{in} = a_i \tag{2}$$

$(i = 1.2.3. \ldots .m)$

Similarly, the total demand at the destination D_j is b_j:

$$x_{1j} + x_{2j} + x_{3j} + \cdots + x_{mj} = b_j \tag{3}$$

$(j = 1.2.3. \ldots .n)$

In addition, the total availability $\sum_{i=1}^{m} a_i$ and the total demand $\sum_{j=1}^{n} b_j$ must be equal, i.e.:

$$\sum_{i=1}^{m} a_i = \sum_{j=1}^{n} b_j \tag{4}$$

These constraints must be satisfied. Furthermore, there is the non-negative constraints:

$$x_{ij} \geq 0 \tag{5}$$

We form a rectangular transportation table where the quantity x_{ij} is assigned in the $(i.j)^{th}$ cell. The unit cost c_{ij} is written in a corner of the $(i.j)^{th}$ cell. If $\sum_{i=1}^{m} a_i =$

$\sum_{j=1}^{n} b_j$ then the problem is called a *balanced problem*. In order to obtain a feasible solution, we need a balanced problem.
A set of non-negative values x_{ij}, which represent the quantity of commodity transported from the i^{th} source to the j^{th} destination $(i = 1.2.3. \dots . m; j = 1.2.3. \dots . n)$ and satisfy the equations 2, 3, 4 and 5, is called a feasible solution to the transportation problem [19]. Table 1 represents a transportation problem table, which all of its parameters are included.

2.2. Item description in mine planning based on SMIPCC as a transportation problem

As it described in the previous section, any transportation problem needs to have specified "sources" and "destinations". In this regards, "sub-phases" of the mining project are introduced as the sources. The term sub-phase is used because of distinguishing it with the "phase" concept in mining [20]. Any sub-phase is a scheduled production of the mine in a certain period of time. Accordingly, a specific tonnage for production is defined as supply i.e.:

S_i = The i^{th} sub-phase of the mine. (6)

a_i = The tonnage produced in the i^{th} sub-phase. (7)

Table 1. A typical table of a transportation problem

Destination

Sources	D_1	D_2		D_j		D_n	Supply
S_1	x_{11} c_{11}	x_{12}		${}_{1j}$ c_{1j}		x_{1n} c_{1n}	a_1
S_2	x_{21} ${}_{21}$	x_{22} ${}_{22}$		${}_{2j}$ c_{2j}		x_{2n} c_{2n}	a_2
S_3	x_{31} ${}_{31}$	x_{32} ${}_{32}$		${}_{3j}$ c_{3j}		x_{3n} c_{3n}	a_3
S_i	x_{i1}	x_{i2} ${}_{2}$		${}_{ij}$ c_{ij}		x_{in} c_{in}	a_i
S_m	${}_{m1}$ ${}_{1}$	${}_{m2}$ 2		${}_{mj}$ ${}_{nj}$		x_{mn} c_{mn}	a_m
Demand	b_1	b_2		b_j		b_n	

Different levels (benches), which the SMIPCC is practically possible to be located, can be supposed as destinations. In this paper, it is assumed that there is only one possible point for setting the SMIPCC in each level i.e.:

D_j = The j^{th} level (bench) of the mine (8)

The surface (D_1) is set as zero and by deepening the pit and creation of new levels, the bench numbers ($D_2 . D_3 . D_4 . \ldots$) will be decreased (-1, -2, -3, …). There are some assumptions for specifying demands which are as follows:

1) It is possible for SMIPCC to be relocated in each sub-phase.
2) In each sub-phase, the mine progresses by one level.
3) Since it is not feasible to send the production of each sub-phase to a further level (because it is not yet operated), it could be only transferred to its previous levels.

As a result, the demand can be defined as:

$b_j =$ The total tonnage that can be sent to the j^{th} level (bench) of the mine (9)

The total operating and capital costs of trucks and SMIPCC (c_{ij}) is set in the transportation problem as the cost of transferring the ore from specific source S_i (sub-phase) to a specific destination D_j (bench number). The goal of this problem is to find a solution in a way that determines x_{ij}. It refers that how many of each sub-phase must be sent to the benches that leads to a minimum amount of total operating costs. In this manner, it is possible that a whole tonnage produced in a sub-phase sent to only one or different benches.

3. Case study

As the case study, a hypothetical copper mine is considered, which is divided into 10 sub-phases. This mine is using a SMIPCC as a transportation system, which is fed directly by trucks. Based on the technical design of the mine, it is possible to relocate the SMIPCC in different levels, which leads to a less traveling distance by trucks but more length of conveyor belt. The objective is to find the optimum location and relocation plan for the SMIPCC that result to the minimum operating costs of trucks and SMIPCC. Some technical features of this mine is mentioned in Table 2. The quantities in the items production planning, SMIPCC and ramp are assumptions. However, in the case of truck type, shovel type and conveyor belt, the quantities are designed based on the relevant handbooks [21,22,23]. Some features and assumptions for trucks and shovels are shown in Table 4. In evaluating the costs of mining, the following assumptions were taken into account:

1) Since the capital cost of the SMIPCC (purchase price) could not be measured, it was not considered in the calculations. Subsequently, the capital cost of trucks (purchase price) was not taken into account as well.

2) While the conveying system of each SMIPCC is one of the most important part of it, the operating costs of SMIPCC refers to the operating costs of conveying system.

3.1. Truck's operating costs

The parameters and quantities that are considered for the operating costs of trucks are mentioned in Table 5. All of these parameters and designs are based on the Caterpillar 777D. Some other operating costs such as maintenance, total fuel costs, oil and lubricants are determined based on the working hours or total traveling distances of truck in each sub-phase [24]. It is important to note that the operating costs of the shovels are not included in the calculations because their quantities will not be affected by transportation system (trucks and SMIPCC) but dependent on the production planning.

Table 2. Technical characteristics of a hypothetical copper mine

Item	Parameter	quantity	unit
Production Planning	Rock density	2.20	t/m^3
	Production per day	100,000	t
	Working hours per day	24	hour
	Working days in month	29	days
SMIPCC	Production capacity	4200	t/hour
Ramp	Ramp grade	10	%
Truck Type	Caterpillar 777D	The quantity differs in each sub-phase	
Shovel Type	Caterpillar 5230 ME	The quantity differs in each sub-phase	
Conveyor Belt	Designed belt speed	600	ft/min
	Length of each conveyor part	100	m
	Lump size	8	in
	Angle of repose	30-45	degree
	Angle of surcharge	20	degree
	Maximum inclination	20	degree
	Percentage of lump on belt	100	%
	Belt width	54	in
	Belt weight	19	lbs/ft
	Cross section of load	2.309	ft^2
	Idler Spacing	3	ft
	Idler diameter	6	in
	Minimum temperature	-30	°C
	Number of return idlers	8	
	Drive efficiency	90	%
	Production capacity	5178	t/h

3.2. SMIPCC's operating costs

These costs are described in Table 6. Some other operating costs such as maintenance and total electricity costs are determined based on the working hours or total length of the belt in each sub-phase [23].

3.3. Sub-phases description and production planning

As it mentioned before, 10 sub-phases is considered for this hypothetical case study. The production in the first sub-phase is considered 18,000,000 tons of ore and its subsequent sub-phases will be reduced by 200,000 tons. For instance, the second sub-phase production would be 17,800,000 tons, the third sub-phase would be 17,600,000 tons and so on (Table 3Table 3).

Table 3. The sub-phases and their relevant production and time planning.

Sub-phases	Duration (months)	Production per sub-phase (ton)
1	6	18000000
2	6	17800000
3	6	17600000
4	6	17400000
5	6	17200000
6	6	17000000
7	6	16800000
8	6	16600000
9	6	16400000
10	6	16200000

Table 4. Truck 777D and shovel 5230 ME features.

Item	Parameter	Quantity	Unit	Reference
Truck 777D	Manoeuvre and unloading time	48	Second	(Caterpillar, 2007)
	Manoeuvre and loading time	140	Second	
	Fill factor	90	%	
	Volume	60.1	m^3	(Caterpillar, 2007)
	Capacity	90.4	ton	
	Fuel consumption (empty truck)	65	lit/hour	
	Fuel consumption (full truck)	85	lit/hour	
Shovel 5230 ME	Fill factor	90	%	
	Bucket capacity	17	m^3	(Caterpillar, 2015)
	Each cycle for filling truck	30	Second	

Table 5. Operating costs of caterpillar 777D truck.

Item	Parameter	Quantity	Unit	Reference
Operating Costs	Tire type	27.00R49 (E4)		(Caterpillar, 2007)
	Tire price	8,000	$	
	Tire life	3400	hour	(Lowrie, 2009)
	Tire cost and repair	2.71	$/h	
	Repair mechanical drive	65	$/h	

Item	Parameter	Quantity	Unit	Reference
	Repair electrical drive	34.6	$/h	
	Fuel price	1	$/lit	
	Labour cost	23	$/hour	

Table 6. Operating costs of SMIPCC

Item	Parameter	Quantity	Unit
Operating Costs	Electricity cost	0.4	$/kWh
	Labour cost	23	$/hour

Each sub-phase is considered in a way that is capable to send the ore to its current or previous benches. As a result, there would be a certain traveling distance by trucks to the SMIPCC, specific location for the SMIPCC and its distance to the surface. As an example, the possible ways for the sub-phases 1, 5 and 10 are depicted in Table 7, Table 8 and Table 9 respectively. As an example, these tables show that if the total production of ore from the sub-phase 10 sent to the SMIPCC location -5 (bench or level), the distance from the face to the SMIPCC that trucks need to cover is 852.5 meters (this equals the average distance that a truck passes in the 10th bench plus traveling four ramps to catch the level -5). In addition, based on the bench's height (in this case is 12.5 meters) and geometrical calculations, the distance from SMIPCC to the surface will be 628 meters (this equals passing the conveyor belt in five ramps to reach the surface). It is important to note that the ramp is considered as the rout of the conveyor belt. In this regards and based on their cycling times, the total number of trucks and shovels in each sub-phase can be calculated (Table 7, Table 8 and Table 9). In this manner, such a table can be described for all the sub-phases and for each, the total operating costs (trucks and SMIPCC) can be calculated.

Operating costs of trucks and SMIPCC in each sub-phase can be calculated based on the parameters that were described in Table 5 and Table 6. Furthermore, these costs are different in each sub-phase regarding to the distances that the ore is transported by trucks or conveyor belt. For instance, Table 10, Table 11 and Table 12 show these costs in the sub-phase 1, 5 and 10 respectively.

Table 7. First sub-phase for the extraction of ore

Sub-phase	Duration (months)	Production (ton)	SMIPCC location (Bench or level)
1	6	18,000,000	0

One way Travel Distance of each Truck to SMIPCC (m)	Distance from SMIPCC to surface (m)	No. of Shovels	No. of Trucks
350	0	2	5

Table 8. Fifth sub-phase for the extraction of ore

Sub-phase	Duration (months)	Production (ton)	SMIPCC location (Bench or level)
5	6	14,000,000	0
5	6	14,000,000	-1
5	6	14,000,000	-2
5	6	14,000,000	-3
5	6	14,000,000	-4

One way Travel Distance of each Truck to SMIPCC (m)	Distance from SMIPCC to surface (m)	No. of Shovels	No. of Trucks
852,5	0	2	8
726,9	126	2	7
601,2	251	2	7
475,6	377	2	6
350,0	502	2	5

Table 9. Tenth sub-phase for the extraction of ore

Sub-phase	Duration (months)	Production (ton)	SMIPCC location (Bench or level)
10	6	9,000,000	0
10	6	9,000,000	-1
10	6	9,000,000	-2
10	6	9,000,000	-3
10	6	9,000,000	-4
10	6	9,000,000	-5
10	6	9,000,000	-6
10	6	9,000,000	-7
10	6	9,000,000	-8
10	6	9,000,000	-9

One way Travel Distance of each Truck to SMIPCC (m)	Distance from SMIPCC to surface (m)	No. of Shovels	No. of Trucks
1480,6	0	2	11
1355,0	126	2	11
1229,4	251	2	10
1103,7	377	2	9
978,1	502	2	9

One way Travel Distance of each Truck to SMIPCC (m)	Distance from SMIPCC to surface (m)	No. of Shovels	No. of Trucks
852,5	628	2	8
726,9	754	2	7
601,2	879	2	7
475,6	1005	2	6
350,0	1131	2	5

3.4. Transportation problem matrix

By knowing the costs of transporting the ore from different sub-phases to any possible location of the SMIPCC (bench), the transportation matrix can be defined. The transportation problem matrix from sub-phase 1 to 10 is shown in Figure 1.

Table 10. First sub-phase operating costs.

From sub-phase	To the bench	Trucks operating costs ($/ton)	Conveyor belt operating costs ($/ton)	Total operating costs ($/ton)
1	0	0.38	0.16	0.54

Table 11. Fifth sub-phase operating costs.

From sub-phase	To the bench	Trucks operating costs ($/ton)	Conveyor belt operating costs ($/ton)	Total operating costs ($/ton)
5	0	0.72	0.16	0.88
5	-1	0.62	0.19	0.80
5	-2	0.56	0.21	0.77
5	-3	0.47	0.24	0.71
5	-4	0.39	0.26	0.65

Table 12. Tenth sub-phase operating and capital costs.

From sub-phase	To the bench	Truck operating costs ($/ton)	Conveyor belt operating costs ($/ton)	Total operating costs ($/ton)
10	0	1.22	0.16	1.38
10	-1	1.15	0.19	1.33
10	-2	1.02	0.21	1.23
10	-3	0.90	0.24	1.14
10	-4	0.84	0.26	1.10
10	-5	0.73	0.29	1.02
10	-6	0.63	0.31	0.94
10	-7	0.57	0.34	0.91
10	-8	0.48	0.36	0.84
10	-9	0.40	0.39	0.79

		Bench Number									
		0 (surface)	-1	-2	-3	-4	-5	-6	-7	-8	-9
sub-phases	1	0,54									
	2	0,62	0,57								
	3	0,71	0,65	0,59							
	4	0,78	0,74	0,68	0,62						
	5	0,88	0,80	0,77	0,71	0,65					
	6	0,99	0,91	0,83	0,80	0,73	0,68				
	7	1,06	1,02	0,93	0,86	0,82	0,76	0,70			
	8	1,18	1,08	1,04	0,96	0,89	0,85	0,79	0,73		
	9	1,31	1,21	1,11	1,07	0,99	0,91	0,88	0,82	0,76	
	10	1,38	1,33	1,23	1,14	1,10	1,02	0,94	0,91	0,84	0,79

Fig. 1. Transportation problem matrix

As it can be seen in Figure 1, some cells are empty because it is practically impossible to send the production of one sub-phase to its further benches, which are not yet operated. On the other hand, for solving this matrix, it is needed that all the cells have a value. In this regards and for empty cells, a bigger value than the maximum operating cost in the table will be assigned that could not be selected as the results, which is finding the minimum operating costs. In this case, the value 2 is chosen (Figure 2). Demand for each column is equal to the total ore that can be sent to its related bench. For instance, in the bench number -3, the total ore production 84,000,000 tons (the total production from sub-phase 4 to 10) can be sent to this location. In addition, supply for each row is equal to the production of its relevant sub-phase; for instance, the supply of the sub-phase 5 would be 14,000,000 tons. Therefore, the Figure 1 would be modified as Figure 2 by adding the demands and the supplies.

4. Models and steps for solving the transportation problem matrix

In the previous section, the transportation problem matrix was established. In this section, the methods for solution of this matrix and finding the optimum plan for location and relocation of the SMIPCC will be explained.

There are different steps for solving a transportation problem, which are briefly described in the following sections:

		Bench Number										
		0 (surface)	-1	-2	-3	-4	-5	-6	-7	-8	-9	Supply
sub-phases	1	0,54	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	18.000.000
	2	0,62	0,57	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	17.800.000
	3	0,71	0,65	0,59	2,00	2,00	2,00	2,00	2,00	2,00	2,00	17.600.000
	4	0,78	0,74	0,68	0,62	2,00	2,00	2,00	2,00	2,00	2,00	17.400.000
	5	0,88	0,80	0,77	0,71	0,65	2,00	2,00	2,00	2,00	2,00	17.200.000
	6	0,99	0,91	0,83	0,80	0,73	0,68	2,00	2,00	2,00	2,00	17.000.000
	7	1,06	1,02	0,93	0,86	0,82	0,76	0,70	2,00	2,00	2,00	16.800.000
	8	1,18	1,08	1,04	0,96	0,89	0,85	0,79	0,73	2,00	2,00	16.600.000
	9	1,31	1,21	1,11	1,07	0,99	0,91	0,88	0,82	0,76	2,00	16.400.000
	10	1,38	1,33	1,23	1,14	1,10	1,02	0,94	0,91	0,84	0,79	16.200.000
Demand		171000000	153000000	135200000	117600000	100200000	83000000	66000000	49200000	32600000	16200000	

Fig. 2. Completed transportation problem (with supplies and demands).

4.1. Find a basic feasible solution

There are different techniques that a basic feasible solution can be obtained. The most important of these techniques are “the north-west corner rule”, “lease-cost method” and “Vogel’s approximation method”. The difference among these methods is the “quality” of the initial basic feasible solution they produce, in the sense that a better starting solution will involve a smaller objective value (minimization problem). In general, the Vogel’s approximation method yields the best starting solution and the north-west corner method yields the worth. However, the latter is easier, quick and involves the least computations to get the initial solution (Kumar Gupta & Hira, 2008).

a) North-west corner rule or north-west corner method (NWCM)

Consider the north-west corner cell (1,1) of the transportation problem matrix. The supply at the source S_1 is a_1 and the demand at the destination D_1 is b_1. Choose the minimum of a_1 and the b_1, say a_1. Allot the quantity a_1 to the (1,1) cell. This is the maximum quantity that can be allotted to the (1,1) cell. Having allotted a_1 to the (1,1) cell, it is found that the total supply at S_1 is exhausted. Hence, no more allocation can be made in the first row. Therefore, $x_{11} = a_1$ and $x_{11} = a_{13} = \cdots = x_{1n} = 0$. Now the demand at D_1 becomes $b_1 - a_1$. In the table, the north-west corner cell is (2,1). As before, choose the minimum of $b_1 - a_1$ and a_2 and allot the quantity in the (2,1) cell. Suppose $b_1 - a_1$ is the minimum. Then allot $b_1 - a_1$to the (2,1) cell and assign zero values to the remaining cells of the first column. Now the supply at S_2 becomes $a_2 - (b_1 - a_1)$. In the new table (2,2) cell becomes the north-west corner cell and allot maximum possible quantity to this cell. Proceeding like this, after a finite number of steps, an initial basic feasible solution will be achieved. In order to have a nondegenerate solution there must be $(m + n + 1)$ basic cells (Iyar, 2008).

b) Least cost method (or matrix minima method or lowest cost entry method)

This method consists in allocating as much as possible in the lowest cost cell/cells and then further allocation is done in the cell/cells with second lowest cost and so on. In case of tie among the cost, the cell with allocation of more number of units can be selected [25].

c) Vogel’s approximation method (VAM) or penalty method or regret method

Vogel’s approximation method is a heuristic method and is preferred to the methods described above. In the transportation matrix if an allocation is made in the second lowest cost cell instead of the lowest, this allocation will have associated a penalty corresponding to the difference of these two costs due to the “loss of advantage”. That is to say, if the difference between the two lowest costs for each row and column is computed, the opportunity cost relevant to each row and column will be found. It would be most economical to make allocation against the row or column with the highest opportunity cost. For a given row or column, the allocation should obviously be made in the least cost cell of that row or column. Vogel’s approximation method, therefore, makes effective use of the cost information and yields a better initial solution than obtained by the other methods. This method consists of the following substeps [25]:

Substep 1) Enter the difference between the smallest and second smallest element in each column below the corresponding column and, the difference between the smallest and the second smallest element in each row to the right of the row. In other words, this difference indicates the unit penalty incurred by failing to make an allocation to the smallest cost cell in that row or column. In case the smallest and second smallest elements in a row/column are equal, the penalty should be taken as zero.

Substep 2) Select the row or column with the greatest difference and allocate as much as possible within the restrictions of the rim conditions to the lowest cost cell in the row or column selected. In case of tie among the highest penalties, select the row or column having minimum cost. In case of tie in the minimum cost, select the cell that can have maximum allocation. Following these rules yields the best possible initial basic feasible solution and reduces the number of iterations required to reach the optimal solution.

Substep 3) Cross of the row or column completely satisfied by the allocation just made. The remaining matrix consist of the rows and columns where allocations have not yet been made, including revised row and column totals which take the already made allocation into account.

Sunstep 4) Repeat steps 1 to 3 until all assignments have been made.

The cost of transportation associated with the above mentioned process will be sum of the assignment of each cell multiplied by its relevant cost.

d) Excel Solver as a linear programming problem

It is possible to solve a transportation problem through the solver of Excel, which set this problem as a linear programming problem as follows:

$$Minimize \quad z = \sum_{i=1}^{m} \sum_{j=1}^{n} c_{ij} x_{ij} \tag{10}$$

$$Subject\ to \quad \sum_{j=1}^{n} x_{ij} = a_i \quad for\ i = 1.2 \ldots .m \tag{11}$$

$$and \quad \sum_{j=1}^{n} x_{ij} \le b_i \quad for\ i = 1.2 \ldots .n \tag{12}$$

$$where \quad x_{ij} \ge 0 \quad for\ all\ i\ and\ j \tag{13}$$

Eq. 11 satisfied the production plan of each sub-phase and Eq.12 covers that each bench only can accept its previous sub-phases as demand.

One of the deficits of this method is that it is not able to solve problems with high amounts of equations and constraints. In this paper, Solver was unable to handle the problem with the sub-phases and benches more than 10; therefore, this number was chosen in calculations.

4.2. Perform optimality test

For the north-west corner rule, least cost method and Vogel's approximation method, making an optimality test is necessary to find whether the obtained feasible solution is optimal or not. An optimality test can of course be performed only on that feasible solution in which:

a) Number of allocations are $m + n - 1$, where m is the number of rows and n is the number of columns.

b) These $(m + n - 1)$ allocations should be in independent positions.

Test procedure for optimality involves examinations of each vacant cell to find whether making an allocation reduces the total transportation cost or not. The two methods that commonly used for this purpose are the stepping-stone method and the modified distribution method (MODI).

While this discussion is not the main part of the paper, interested readers are referred to the related sources for more details about the transportation problem and its solutions [19; 25; 26].

5. Results and discussion

In this paper, finding the optimum solution for the transportation problem matrix is performed by Excel Solver. There are also other software (e.g. TORA), which are capable to solve these types of problems. However, the disadvantages of both tools is their incapability to solve big problems (with a high number of supplies and demands). This is the main reason that why the case study was chosen as a small example with just 10 sources and 10 destination. It is also possible to divide a big matrix to smaller subsequent parts but this may not lead to an optimal solution.

After defining the transportation problem as a linear programming problem and solving through the Excel Solver, the assignment results of different sources (sub-phases) to different destinations (benches) were calculated, which is shown in Fig. 3. As it can be seen in this figure, the minimum operating costs happen when the SMIPCC in each sub-phase relocated to its subsequent bench. Since the operating costs of The SMIPCC is lower than trucks (Table 10, Table 11 and Table 12), obviously it is preferable that use more length of conveyor belts instead of trucks for transferring the ore. In addition, these operating costs are increasing in columns, which means by deepening the mine, the operating costs are likewise increased. However, they are decreasing in rows, which means that by reducing the distance between one specific sub-phase and the SMIPCC, the operating costs are decreased. As a results, the lowest operating costs are in the $(1,1)^{th}$, $(2,2)^{th}$, …, $(10,10)^{th}$ cells. The optimum solution, which is the minimum total operating costs is 112,910,281 dollars. Since each sub-phase lasts six months, the SMIPCC needs to be relocated in this period. In this regards, two important points need to be considered:

1-The relocation cost of the SMIPCC is not considered in the calculations.

2- Such a movement through the project is technically possible.

3- These calculations were performed in a deterministic way and by constant values.

	Bench Number										
sub-phases	0 (surface)	-1	-2	-3	-4	-5	-6	-7	-8	-9	a_i
1	18000000	0	0	0	0	0	0	0	0	0	18000000
2	0	17800000	0	0	0	0	0	0	0	0	17800000
3	0	0	17600000	0	0	0	0	0	0	0	17600000
4	0	0	0	17400000	0	0	0	0	0	0	17400000
5	0	0	0	0	17200000	0	0	0	0	0	17200000
6	0	0	0	0	0	17000000	0	0	0	0	17000000
7	0	0	0	0	0	0	16800000	0	0	0	16800000
8	0	0	0	0	0	0	0	16600000	0	0	16600000
9	0	0	0	0	0	0	0	0	16400000	0	16400000
10	0	0	0	0	0	0	0	0	0	16200000	16200000
b_j	171000000	153000000	135200000	117600000	100200000	83000000	66000000	49200000	32600000	16200000	

Total Transportation Cost 112910281 $

Fig. 3. The solution of transportation problem for 10 sub-phases and 10 benches

Therefore, the location and relocation plan for this project can be described as Table 13.

5.1. Sensitivity analysis

The two most important parameters that have significant impacts in the operating costs of trucks and SMIPCC are fuel price and electricity price respectively. Any changes in these parameters can affect the total costs and consequently, the relocation plan of the SMIPCC. Therefore, these parameters are chosen for a sensitivity analysis and depicting the changes in both costs and planning. For this purpose, different quantities of the fuel and electricity costs were examined. For instance, Figure 4 and Figure 5 show the operating costs per ton of ore and the relocation plan of SMIPCC with the fuel price of 1.2 $/lit and the electricity price 0.4 $/kWh.

As shown in the Figure 4, the total operating costs per ton is naturally increased and the process of increasing and decreasing of the costs, is the same as Figure 2. As a result, expectedly there would not be any changes in the relocation plan of the SMIPCC (Figure 5).

Table 13. The location and relocation plan of the SMIPCC

Sub-phase	Time (month)		Location and Relocation Plan (bench)
	From	To	
1	0	6	0 (surface)
2	7	12	-1
3	13	18	-2
4	19	24	-3
5	25	30	-4
6	31	36	-5
7	37	42	-6

Sub-phase	Time (month)		Location and Relocation Plan (bench)
	From	To	
8	43	48	-7
9	49	54	-8
10	55	60	-9

sub-phases	Bench Number									
	0 (surface)	-1	-2	-3	-4	-5	-6	-7	-8	-9
1	0,56	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00
2	0,65	0,59	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00
3	0,74	0,68	0,62	2,00	2,00	2,00	2,00	2,00	2,00	2,00
4	0,81	0,77	0,70	0,65	2,00	2,00	2,00	2,00	2,00	2,00
5	0,91	0,84	0,80	0,73	0,67	2,00	2,00	2,00	2,00	2,00
6	1,03	0,94	0,86	0,83	0,76	0,70	2,00	2,00	2,00	2,00
7	1,10	1,06	0,97	0,89	0,86	0,79	0,73	2,00	2,00	2,00
8	1,22	1,13	1,08	1,00	0,92	0,88	0,82	0,76	2,00	2,00
9	1,36	1,25	1,16	1,11	1,03	0,95	0,91	0,85	0,79	2,00
10	1,44	1,38	1,28	1,18	1,14	1,06	0,98	0,94	0,87	0,82

Fig. 4 Total operating costs per ton of ore production (fuel price 1.2 $/lit and electricity price 0.4 $/kWh)

sub-phases	Bench Number										a_i
	0 (surface)	-1	-2	-3	-4	-5	-6	-7	-8	-9	
1	18000000	0	0	0	0	0	0	0	0	0	18000000
2	0	17800000	0	0	0	0	0	0	0	0	17800000
3	0	0	17600000	0	0	0	0	0	0	0	17600000
4	0	0	0	17400000	0	0	0	0	0	0	17400000
5	0	0	0	0	17200000	0	0	0	0	0	17200000
6	0	0	0	0	0	17000000	0	0	0	0	17000000
7	0	0	0	0	0	0	16800000	0	0	0	16800000
8	0	0	0	0	0	0	0	16600000	0	0	16600000
9	0	0	0	0	0	0	0	0	16400000	0	16400000
10	0	0	0	0	0	0	0	0	0	16200000	16200000
b_j	171000000	153000000	135200000	117600000	100200000	83000000	66000000	49200000	32600000	16200000	

Total Transportation Cost 117275061 $

Fig. 5. Relocation plan of the SMIPCC (fuel price 1.2 $/lit and electricity price 0.4 $/kWh).

Let for the second try, consider the fuel and electricity price as 1 $/lit and 2.2 $/kWh respectively. Its relevant operating costs per ton and relocation plan are illustrated in Figure 6 and Figure 7. In spite of the previous try, with this condition of prices, the total operating costs of each sub-phase to the benches are relatively close to each other. In fact, the price of electricity is increased in a level that cannot firstly compete with the price of fuel anymore and secondly, propose relocation of the SMIPCC as an alternative for trucks. In this case, not only the operating costs are increased in comparison with previous state, but also the SMIPCC needs to be relocated in a different order (relocating it in each sub-phases 1, 2 and 3 and relocating to the surface at the sub-phase 4). This example clearly shows the effect of the fuel and electricity prices in the SMIPCC relocation plan.

As the third attempt, let consider the fuel price and the electricity price as 1 $/lit and 4 $/kWh. The results of the operating costs per ton and the relocation plan of the SMIPCC are illustrated in the Figure 8 and Figure 9 respectively. These figures represent that the operating costs of the SMIPCC are considerably high in which it would be better to extract the ore by trucks in all the sub-phases and not to change the location of the SMIPCC (keep it at the surface).

sub-phases	Bench Number									
	0 (surface)	-1	-2	-3	-4	-5	-6	-7	-8	-9
1	0,771	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000
2	0,855	0,850	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000
3	0,946	0,934	0,930	2,000	2,000	2,000	2,000	2,000	2,000	2,000
4	1,008	1,025	1,013	1,009	2,000	2,000	2,000	2,000	2,000	2,000
5	1,110	1,087	1,105	1,093	1,089	2,000	2,000	2,000	2,000	2,000
6	1,220	1,190	1,167	1,184	1,173	1,168	2,000	2,000	2,000	2,000
7	1,290	1,300	1,269	1,246	1,264	1,252	1,248	2,000	2,000	2,000
8	1,411	1,369	1,379	1,349	1,326	1,344	1,332	1,327	2,000	2,000
9	1,540	1,490	1,448	1,459	1,428	1,405	1,423	1,411	1,407	2,000
10	1,616	1,619	1,570	1,528	1,538	1,508	1,485	1,503	1,491	1,487

Fig. 6.The total operating costs per ton of ore production
(fuel price 1 $/lit and electricity price 2.2 $/kWh).

sub-phases	Bench Number										a_i
	0 (surface)	-1	-2	-3	-4	-5	-6	-7	-8	-9	
1	18000000	0	0	0	0	0	0	0	0	0	18000000
2	0	17800000	0	0	0	0	0	0	0	0	17800000
3	0	0	17600000	0	0	0	0	0	0	0	17600000
4	17400000	0	0	0	0	0	0	0	0	0	17400000
5	0	17200000	0	0	0	0	0	0	0	0	17200000
6	0	0	17000000	0	0	0	0	0	0	0	17000000
7	0	0	0	16800000	0	0	0	0	0	0	16800000
8	0	0	0	0	16600000	0	0	0	0	0	16600000
9	0	0	0	0	0	16400000	0	0	0	0	16400000
10	0	0	0	0	0	0	16200000	0	0	0	16200000
b_j	171000000	153000000	135200000	117600000	100200000	83000000	66000000	49200000	32600000	16200000	

Total Transportation Cost 191472300 $

Fig. 7. Relocation plan of the SMIPCC (fuel price 1 $/lit and electricity price 2.2 $/kWh).

sub-phases	Bench Number									
	0 (surface)	-1	-2	-3	-4	-5	-6	-7	-8	-9
1	1,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00
2	1,09	1,13	3,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00
3	1,18	1,22	1,27	3,00	3,00	3,00	3,00	3,00	3,00	3,00
4	1,24	1,31	1,35	1,40	3,00	3,00	3,00	3,00	3,00	3,00
5	1,34	1,37	1,44	1,48	1,53	3,00	3,00	3,00	3,00	3,00
6	1,45	1,47	1,50	1,57	1,61	1,66	3,00	3,00	3,00	3,00
7	1,52	1,58	1,61	1,63	1,70	1,74	1,79	3,00	3,00	3,00
8	1,64	1,65	1,72	1,74	1,77	1,83	1,87	1,92	3,00	3,00
9	1,77	1,77	1,78	1,85	1,87	1,90	1,97	2,01	2,05	3,00
10	1,85	1,90	1,91	1,92	1,98	2,00	2,03	2,10	2,14	2,18

Fig. 8. The total operating costs per ton of ore production
(fuel price 1 $/lit and electricity price 4 $/kWh).

sub-phases	Bench Number										a_i
	0 (surface)	-1	-2	-3	-4	-5	-6	-7	-8	-9	
1	18000000	0	0	0	0	0	0	0	0	0	18000000
2	17800000	0	0	0	0	0	0	0	0	0	17800000
3	17600000	0	0	0	0	0	0	0	0	0	17600000
4	17400000	0	0	0	0	0	0	0	0	0	17400000
5	17200000	0	0	0	0	0	0	0	0	0	17200000
6	17000000	0	0	0	0	0	0	0	0	0	17000000
7	16800000	0	0	0	0	0	0	0	0	0	16800000
8	16600000	0	0	0	0	0	0	0	0	0	16600000
9	16400000	0	0	0	0	0	0	0	0	0	16400000
10	16200000	0	0	0	0	0	0	0	0	0	16200000
b_j	171000000	153000000	135200000	117600000	100200000	83000000	66000000	49200000	32600000	16200000	

Total Transportation Cost 239451005 $

Fig. 9. Relocation plan of the SMIPCC (fuel price 1 $/lit and electricity price 4 $/kWh).

5.1.1. The constant electricity price and the fuel price changes

When the electricity price is constant (0.4 $/kWh) and the fuel price changes, it is always preferable to relocate the SMIPCC in each sub-phase to the next bench. In this case, the SMIPCC will be located at different benches, which leads to the minimum operating costs (Table 14).

5.1.2. The constant fuel price and the electricity price changes

As it is shown in Table 15, when the fuel price is constant (1 $/lit) and the electricity price changes up to 1.8 time of the fuel price, the relocation of the SMIPCC will be done in each sub-phases. However, when the electricity price is 2.2 times of the fuel price, the sub-phase 4 must be sent to the surface (the location of the SMIPCC) that concludes the minimum operating costs. Finally, when the electricity price is more than 4 times of the fuel price, the relocation of the SMIPCC would ne be economic and it must be kept at the surface.

Table 14. The relocation plan in constant electricity price and changing fuel price

Fuel Price ($/lit)	0,2	0,6	1	1,4	1,8	2,2	2,6	3	3,4	3,8	4,2
Electricity Price ($/kWh)	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4
from sub-phase	to the bench										
1	0	0	0	0	0	0	0	0	0	0	0
2	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
3	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
4	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3
5	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4
6	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5
7	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6
8	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7
9	-8	-8	-8	-8	-8	-8	-8	-8	-8	-8	-8
10	-9	-9	-9	-9	-9	-9	-9	-9	-9	-9	-9
Total Transportation Cost ($)	95451160	104180721	112910281	121639841	130369401	139098961	147828522	156558082	165287642	174017202	182746763

Table 15. The relocation plan in the condition of the fuel price and the electricity price increasing and decreasing

Fuel Price ($/lit)	1	1	1	1	1	1	1	1	1	1	1
Electricity Price ($/kWh)	0,2	0,6	1	1,4	1,8	2,2	2,6	3	3,4	3,8	4,2
from sub-phase	to the bench										
1	0	0	0	0	0	0	0	0	0	0	0
2	-1	-1	-1	-1	-1	-1	0	0	0	0	0
3	-2	-2	-2	-2	-2	-2	-1	0	0	0	0
4	-3	-3	-3	-3	-3	0	0	0	0	0	0
5	-4	-4	-4	-4	-4	-1	-1	-1	0	0	0
6	-5	-5	-5	-5	-5	-2	-2	-2	0	0	0
7	-6	-6	-6	-6	-6	-3	-3	0	0	0	0
8	-7	-7	-7	-7	-7	-4	-4	-1	-1	0	0
9	-8	-8	-8	-8	-8	-5	-5	-2	-2	-1	0
10	-9	-9	-9	-9	-9	-6	-6	-3	0	0	0
Total Transportation Cost ($)	104159589	121660972	139162356	156663739	174165123	191472300	204671303	215821156	225690921	234969284	243873402

6. Conclusion

This paper introduced a new definition of optimum location and relocation plan of the SMIPCC in open pit mines. This fulfilled by defining this problem as a transportation problem and minimizing the operating costs. Sources and supplies were considered as sub-phases and their related production respectively while destination and demands were the benches and the total quantity of a production that each level of the mine (benches) can accept respectively. A case study of a hypothetical open pit mine with 10 sub-phases and 10 benches was considered and the model was implemented. Solving this model was done through the Excel Solver and transforming it to a linear programming. It was shown that it could efficiently determine the optimum location and the relocation plan of the SMIPCC. However, it was discussed that this solution is highly depended on the inputs especially fuel and electricity prices. There are also some assumptions, which are not considering the relocation cost, constant quantities and not considering the uncertainties in inputs.

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