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Modeling and Optimization of Truck-Shovel Allocation to Mining Faces in Cement Quarry

K.S. Shah[1]* and S.U. Rehman[1]

Department of Mining Engineering, University of Engineering and Technology Peshawar, Peshawar, Pakistan

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Abstract

Truck and shovel are the most common raw material transportation system used in the cement quarry operations. One of the major challenges associated with the cement quarry operations is the efficient allocation of truck and shovel to the mining faces. In order to minimize the truck and shovel operating cost, subject to quantity and quality constraints, the mixed integer linear programing (MILP) model for truck and shovel allocation to mining faces for cement quarry is presented. This model is implemented using the optimization IDE tool GUSEK (GLPK under SciTE Extended Kit) and the GLPK (GNU Linear Programming Kit) standalone solver. The MILP model is applied to an existing cement quarry operation, the Kohat cement quarry located at Kohat (Pakistan) as a case study. The analysis of the results of the relating case study reveals that significant gains are achievable through employing the MILP model. The results obtained not only show a significant cost reduction but also help in achieving a better coordination among the quarry and quality department.

1. Introduction

The cement manufacturing process starts with raw material extraction and transportation from quarry. In a cement quarry operation, a material handling system is composed of loading, hauling, and dumping. Transportation of the materials from the mining faces to the crusher is accomplished by truck-shovel, rail, belt conveyor, and hydraulic transport. Truck and shovel is one of the most commonly used raw material transportation system in cement quarry. Loading is carried out through shovels and loaders, while trucks are mostly used for transportation. Truck and shovel allocation and dispatching are two distinct processes. This research work is mainly focused on the truck and shovel allocation to the mining faces, which are typically attained at the commencement of a shift. Usually the dispatchers allocate truck and shovel at the beginning of a shift time based on the experience and data. In this case, the efficiency of truck and shovel depends on the dispatcher's experience, which is variant between shifts. The dispatcher's required skills for an efficient allocation of truck and shovel are subject to a consistent truck and shovel dispatching training. However, this does not guarantee the consistency and optimal truck and shovel allocation [1]. The transported raw materials from quarry operations are blended in appropriate proportions to meet the stoichiometric needs, i.e. the required quality and quantity of the major and minor oxides [2].

In cement manufacturing, raw mix is a mixture of calcareous and argillaceous minerals reacting together to form calcium silicate. These calcareous and argillaceous minerals consist of major and minor oxides. These oxides vary within the quarry and from one quarry to another. The quality of the final product, i-e. Cement, depends on the provision of raw materials fulfilling the strict quantity and quality requirements. For this purpose, the presented model consists of quality and quantity constraints because the objective of truck and shovel allocation is not only to minimize the operating cost but also to fulfill the quality and quantity requirements associated with the cement

Corresponding author: kausarsultanshah@gmail.com (K. Sultan Shah).

quarry operations [3, 4]. In the past decades, simulation has become one of the most favored tool because it deals with complex models and is easy to use for material handling and transportation, mine planning, and production scheduling [5].

Nowadays, an open-pit mine consists of large amounts of the haulage system for raw material handling, which becomes more complex with the passage of mining time. Running an effective haulage system effectively requires a proper planning, development, and operating maintenance, which can be accomplished using the simulation and optimization techniques. The optimization problems relating to these aspects optimize the haulage system by providing valuate different feasible operating scenarios [6]. Studies on truck and shovel or only truck allocation have been carried out by numerous authors. Nenonen *et al.* [7] have worked on the truck and shovel operation system in an open-pit mine using the interactive computer model. Gershon [8] has developed a model that described cement operation from quarry to the market. He accomplished his work using simultaneous and optimization. Li [9] has presented a linear programming approach for the optimum control of the truck and shovel operations in open-pit mining. Muduli [10] has presented a close queuing network model for a truck and shovel system with several job classes. Ercelebi [4] has described a truck and shovel model and optimization of truck dispatching and allocation under several operating conditions. Sahoo [11] has presented a model to minimize the number of allocated trucks to the number of shovels, while keeping ore grade and production constraints. Chang *et al*. [1] has presented a model for truck allocation to shovels incorporating idle probability of shovel. This model was formulated to minimize the number of trucks allocated to an available set of shovels subject to quantity of production and ore grade constraint. Dong [12] has used the queueing theory to model and optimize the truck and shovel system for open-pit mines. The queueing model revealed that the type of shovel utilization, queue length, and production were dependent on the number of trucks in the fleet. Upadhuay and Askari [5] have presented a mixed integer linear goal programming (MILGP) model to optimize the truck and shovel dispatch system in open-pit mines. The objectives of the models were to minimize the operating cost, maximize production, minimize deviation from required grade, and meet the amount of materials required by the plant.

Torkamani [6] has developed a theoretical model for the truck and shovel allocation to the mining faces. The model was prepared for open-pit mining operations and was not solved using an optimization tool. In this research work, the Torkamani model was analyzed, modified, and implemented in the cement quarry operations. At the end, the model was solved using the optimization tool solver GUSEK. A mixed integer linear programming model was developed and used to analyze this system. The most significant feature in every operation is profitability. The equipment's productivity is one of the key factors of profitability. To increase profitability, optimization of the truck-shovel combination and allocation can be used. Therefore the goal of this model is to minimize the cost, while meeting the quantity and quality requirements [4, 11].

2. Materials and Methods

Nowadays the mining companies try to allocate the truck/shovel fleet system in such a way to minimize the operating cost. One of the important parameters involved in surface mine design, material handling, and hauling system is the truck/shovel allocation [6]. In Pakistan, the truck/shovel fleet system in combination with a front-end loader is mostly used. Unfortunately, there is no proper planning related truck/shovel allocation to the mining faces and benches. Since there is a significant cost involved with the truck/shovel operation, truck/shovels should be allocated with such an arrangement that reduces the operating, hauling, and maintenance costs, while meeting the desired quantity and quality requirements of raw materials [13]. In this work, a model was presented to demonstrate the application of optimization of truck shovel allocation to the mining faces and benches. Also optimization of this allocation problem was carried out using an optimization tool through a real time case study to handle the raw materials required for cement manufacturing at the optimum cost and within the required quality and quantity. In order to solve the truck-shovel allocation problem, the required data was collected from the Kohat Cement Company, LTD (KCCL).

2.1. Allocation Problem

This research work is based on the analysis, modification, and implementation of the model for cement quarry operations. Therefore, the considered grade of raw material is of two types (low- and high-grade), and the mined material will be hauled to the crusher, and hence, there is only one destination for truck, which is the crusher. The material should be handled in an appropriate way to meet the quality constraint. Deviation from the target production leads to penalty that includes extra cost. The cost of truck moving from the face to the crusher and the cost of shovel moving from one face to another is also considered. Other suppositions made while developing the MILP model are:

1. At each specific period, the mining faces are available for extraction.
2. The crusher capacity is in the limit of maximum and minimum.
3. Certain types of truck can work with certain types of shovel.
4. At the beginning, the number of available truck and shovel will be known.
5. The loading capacities with shovel maximum and minimum production capacity are known.
6. Only one shovel is assigned to each mining face at the same time.
7. Each shovel can work at one mining face at the same time.
8. Shift time for the model.

3. Application of GUSEK

In Gusek, by using the GLPK language, sets and variables of data, parameters, and constraint were defined. Furthermore, data about the number of truck and shovel, required production, trip cost of shovel from current position to face, trip cost truck type, deviation cost, truck cycle time, maximum capacity of crusher, maximum shovel production capacity, tonnage of material at face, grades of material face, and compatibility of truck type with shovel is given by Equation 1.

$$\text{Match Factor} = \frac{\text{total numbers of trucks}}{\text{number of loading units}} * \frac{\text{loading cycle time}}{\text{truck cycle time}} \tag{1}$$

The shovel capacity is time-based productivity (capacity). In this model, the shovel capacity is considered for a shift. The following formulas are used to calculate the shovel overall productivity:

$$\text{Bulk density} = \gamma_e = \frac{\delta_e}{k_e} \tag{2}$$

where $\delta_e =$ Specific gravity, $k_e =$ Swelling factor;

$$\text{Bulk density} = c_r = v_r * \gamma_e \tag{3}$$

where $v_r =$ volumetric capacity of shovel;

$$\text{Number of required buckets to fill truck} = N_b = \frac{v_b}{v_r} \tag{4}$$

where $v_b =$ volume of the truck bed;

$$\text{Total efficiency of shovel} = E_{ef} = k_u * k_{eo} * k_m * D \tag{5}$$

where k_u = Utilization, k_u = work time/total planned time, k_m = mechanical availability ; D = coefficient of truck for every 5 minutes, k_{eo} = efficiency of the machine operator;

$$\text{Time based Productivity of shovel} = \frac{60 * V_c * E_{ef} * B_f}{T_c * K_e} \tag{6}$$

where v_c = volumetric capacity of the shovel bucket, B_f = bucket factor (0-0.4); T_c = cycle time.

4. Mathematical Programming

4.1. MILP Formulation

4.1.1. Set

Set L = {1……… L}	*L represents the material grade*
Set I = {1……......I}	*I represents the mining faces*
Set J = {1………J}	*J represents the shovels*
Set K = {1……. K}	*K represents the truck type*

4.1.2. Indices

l ε L	*Material (limestone raw material) grade index*
i ε I	*Mine face index*
j ε J	*Shovel index*
k ε K	*Truck type index*

4.1.3. Parameters

TC_{ij}	Trip cost of shovel j to face i from current location ($ (US dollar)).
$TRCL_{ik}$	Transportation cost low-grade material of truck type *k* from *i* to crusher ($).
$TRCH_{ik}$	Transportation cost high-grade material of truck type *k* from *i* to crusher ($).
MAT_i	Material (limestone is divided into two types of materials of low- and high-grade) type at *i*.If the raw material is of low grade, its value is 0, and if high grade, it is 1.
DC	Deviation cost from target production ($. per ton).
T	Shift time (hours).
P_{max}	Crusher maximum processing capacity (tons/day).
P_{min}	Crusher minimum processing capacity (tons/day).
NUM_k	Number of trucks available of type *k*.

AVL_i^{face} ε {0, 1}	Available mining face *i*. *i* is equal to 1 if mining face is available otherwise it is 0.
AVL_j^{shovel} ε {0, 1}	Available mining face *j*. *j* is equal to 1 if shovel is available otherwise, it is 0.
CT_{ik}^{l}	Cycle time for truck *k* moving from face *i* containing low-grade material to crusher (minutes).
CT_{ik}^{h}	Cycle time for truck *k* moving from face *i* containing high-grade material to crusher (minutes).
$SHCAP_j^{max}$	Shovel *j* maximum production capacity (tons per hour).
$SHCAP_j^{min}$	Shovel *j* minimum production capacity (tons per hour).
$TRCAP_k^l$	Truck *k* capacity when transferring low-grade material (tons).
$TRCAP_k^h$	Truck *k* capacity when transferring high-grade material (tons).
LG_i	Low-grade raw material at the mining face *i* (tons).
HG_i	High-grade raw material at the mining face *i* (tons).
UB_i	Upper bound of material grade blending for material grade *l* (%).
LB_i	Lower bound of material grade blending for material grade *l* (%).
GR	Balance of chemical composition in cement raw material.
$COMP_{jk}$ ε [5]	Truck of type k compatibility with shovel j; its value is 1 if both truck and shovel are compatible; if not, it is equal to 0.

4.1.4. Decision Variables

a_{ij}	$\begin{cases} 1\ if\ shovel\ j\ is\ assigned\ to\ mining\ face\ i \\ 0,\ otherwise \end{cases}$
n_{ik}^{l}	Decision variable representing number of trips of *k* type of truck from mining face *i* to the crusher carrying low-grade material.
n_{ik}^{h}	Decision variable representing number of trips of *k* type of truck from mining face *i* to the crusher carrying high-grade material.
x_i	Extracted tonnage of material from mining face *i* (tons).

4.1.5. Objective Function

$$\text{Minimize } Z = \sum_{i\in I}\sum_{j\in J} T_{c_{ij}}.a_{ij} + \sum_{i\in I}\sum_{k\in K} TRCL_{ik}.n_{ik}^{l} + \sum_{i\in I}\sum_{k\in K} TRCH_{ik}.n_{ik}^{h} + (dc).\{P_{max} - (\sum_{i\in I} MAT_i.x_i)\} \quad (7)$$

4.1.6. Constraints

$$\sum_{j\in J} a_{ij} = 1 \qquad \forall j \in J \qquad (8)$$

$$\sum_{j\in J} a_{ij} \le 1AVL_i^{face} \qquad \forall j \in J \qquad (9)$$

$$\sum_{i\in I} a_{ij} \le 1AVL_j^{shovel} \qquad \forall i \in I \qquad (10)$$

$$CT_h^{ik}.n_h^{ik} \le 60 * T * NUM_k * MAT_i \qquad \forall i \in I, j \in J \qquad (11)$$

$$CT_l^{ik}.n_l^{ik} \le 60 * T * NUM_k * MAT_i \qquad \forall i \in I, j \in J \qquad (12)$$

$$\sum_{i\in I} n_l^{ik} * CT_l^{ik} + \sum_{i\in I} n_h^{ik} * CT_h^{ik} \le 60 * T * NUM_k \qquad \forall k \in K \qquad (13)$$

$$x_i \le \sum_{j\in J} T * SHCAP_j^{\max} * a_{ij} \qquad \forall i \in I \qquad (14)$$

$$\sum_{i\in I} x_i.MAT_i \le P_{\max} \qquad (15)$$

$$\sum_{i\in I} x_i.MAT_i \ge P_{\min} \qquad (16)$$

$$x_i * MAT_i \le LG_i \qquad \forall i \in I \qquad (17)$$

$$x_i * MAT_i \le HG_i \qquad \forall i \in I \qquad (18)$$

$$x_i = \sum_{k\in K} TRCAP_l^{ik} * n_l^{ik} + \sum_{k\in K} TRCAP_h^{ik} * n_h^{ik} \qquad \forall i \in I \qquad (19)$$

$$\sum_{i\in I} GR_{il} * x_i \le \sum_{i\in I} UB_l * x_i \qquad \forall l \in L \qquad (20)$$

$$\sum_{i\in I} GR_{il} * x_i \ge \sum_{i\in I} LB_l * x_i \qquad \forall l \in L \qquad (21)$$

$$n_l^{ik} \le \sum_{j\in J} a_{ij} * COMP_{jk} \qquad \forall i \in I, k \in K \qquad (22)$$

$$n_h^{ik} \le \sum_{j\in J} a_{ij} * COMP_{jk} \qquad \forall i \in I, k \in K \qquad (23)$$

$$a_{ij} \in \{0,1\} \qquad \forall i \in I, j \in J \qquad (24)$$

$$n_h^{ik}, n_l^{ik} \in Z \qquad \forall i \in I, k \in K \qquad (25)$$

$$x_i \ge 0 \qquad \forall i \in I \qquad (26)$$

Equation (7) represents the objective function. The objective function of this MILP model tries to minimize the truck/shovel cost. In Equation (7), the first term represents the total trip cost of shovel moving from the current location to a mining face. The second and third term represent the truck travelling cost from the face to the crusher. In Equation (7), the last term represents the negative deviation cost from the required production.

Equations (8) and (9) are two constraints to represent that each shovel can be working at one mining face. Equation (10) represents that two shovels cannot be assigned to one mining face. Equation (11) defines the limits of number of trips of trucks from face to the crusher carrying high-grade raw materials, while Equation (12) is for low-grade raw materials. In Equation (13), the constraint represents the total number of trips made by each type of truck, which should be less than or equal to the total possible trips by that truck. Equation (14) ensures that the production of each mining face should be equal to or less than the maximum production capacity of shovel assigned to that mining face. The two constraints in Equations (15) and (16) keep the production amount of raw materials that should not be less or greater than the processing capacity of the crusher. Equations (17) and (18) keep the production amount of raw materials less than the amount of materials available. Equation (19) shows that the total production of each mining face is related to the number of trips made by the truck fleet. Equations (20) and (21) ensure the upper and lower bounds of raw material indices. GR represents the balance of chemical composition in the cement raw material. Equations (22) and (23) ensure the compatibility of the type of truck with shovel. Any incompatibility will lead to non-assignment of the truck to the shovel. Equations (24), (25), and (26) represent the different types of decision variables.

4.1.7. Raw material quality constraints

In cement manufacturing, one of the most significant tasks is to prepare raw mix from the run of mine material prior to cement production. In cement quarry planning, the truck and shovel allocation to the mining faces is correlated to the raw material quality. The objective here is to allocate truck and shovel to the faces in such way that the resulting raw mix meets both the quality and quantity requirements.

In order to produce the final product, i.e. cement, the required quantity and quality of various oxides (calcium (CaO), iron (Fe_2O_3), silica (SiO_2), and alumina (Al_2O_3)) is essential [2]. Following LSF (lime saturation factor), SR (silica ratio) and AM (alumina modulus) are the indices that are used to achieve the quality of the final product and are computed using Equations (27), (28), and (29).

$$LSF = \frac{CaO}{2.80SiO_2 + 1.18Al_2O_3 + 0.65Fe_2O_3} \quad \text{Range (0.845-0.9)} \qquad (27)$$

$$SR = \frac{SiO_2}{Al_2O_3 + Fe_2O_3} \quad \text{Range (2.6-2.9)} \qquad (28)$$

$$AM = \frac{Al_2O_3}{Fe_2O_3} \quad \text{Range (1.5-2.0)} \qquad (29)$$

It is pertinent to mention that the individual major oxides must be kept within the limits, i.e. CaO (40-42%), SiO_2 (14-15%), Al_2O_3 (2.7-3.4%), and Fe_2O_3 (1.65-2.17%) [3]. After a complete burning of raw material/mix in the cement kiln, the hydraulic material is produced, also known as “clinker”. The clinker consists of the compounds tricalcium silicate also known as alite/C_3S ($3CaO.SiO_2$), dicalcium silicate also referred to as belite/C_2S ($2CaO.SiO_2$), tricalcium aluminate also called celite/C_3A ($3CaO.Al_2O_3$), and tetracalcium aluminoferrite also called brownmillirite/C_4AF ($4CaO.Al_2O_3$) [3].

$$C_3S = 4.071 \times CaO - 7.6 \times SiO_2 - 6.718 \times Al_2O_3 - 1.43 \times Fe_2O_3 \quad \text{Range (30-35\%)} \qquad (30)$$

$$C_2S = -3.071 \times CaO + 8.6 \times SiO_2 + 5.068 \times Al_2O_3 - 1.079 \times Fe_2O_3 \quad \text{Range (15-20\%)} \qquad (31)$$

$$C_3A = 2.65 \times Al_2O_3 - 1.692 \times Fe_2O_3 \quad \text{Range (6-8\%)} \qquad (32)$$

$$C_4AF = 3.043 \times Fe_2O_3 \quad \text{Range (4-9.6\%)} \qquad (33)$$

These compounds in Equations 30, 31, 32, and 33 are also used to achieve the balance of the major oxides [3]. In this work, two objectives were considered, i.e. the percentage of ingredient in limestone samples as well as the percent content of major oxides in additives from the market. In order to fulfill the raw material quality constraint, raw mix is design using the Microsoft excel solver.

5. Testing and debugging program

After coding and compiling the program, testing and debugging is required to remove any bugs or errors. Testing and debugging in the program can be performed manually or automated by a tester. If any bugs (errors) are found in the program, they must be removed, and the testing process must be repeated. For this algorithm, the manual method is used to calculate the values using excel, and the acquired results are compared with the test run results. The values found are the same, which means that the program is computed correctly.

6. Model implementation

6.1. Field Description

The MILP model given is implemented through a case study of Kohat cement quarry located in Kohat, Khyber Pakhtunkhwa (Pakistan), given in Figure 1. The Kohat Cement Company Ltd (KCCL) was established in 1980. It is located at the foot of the Kohat Hills and on the Kohat-Pindi Road, and has abundant limestone deposits.

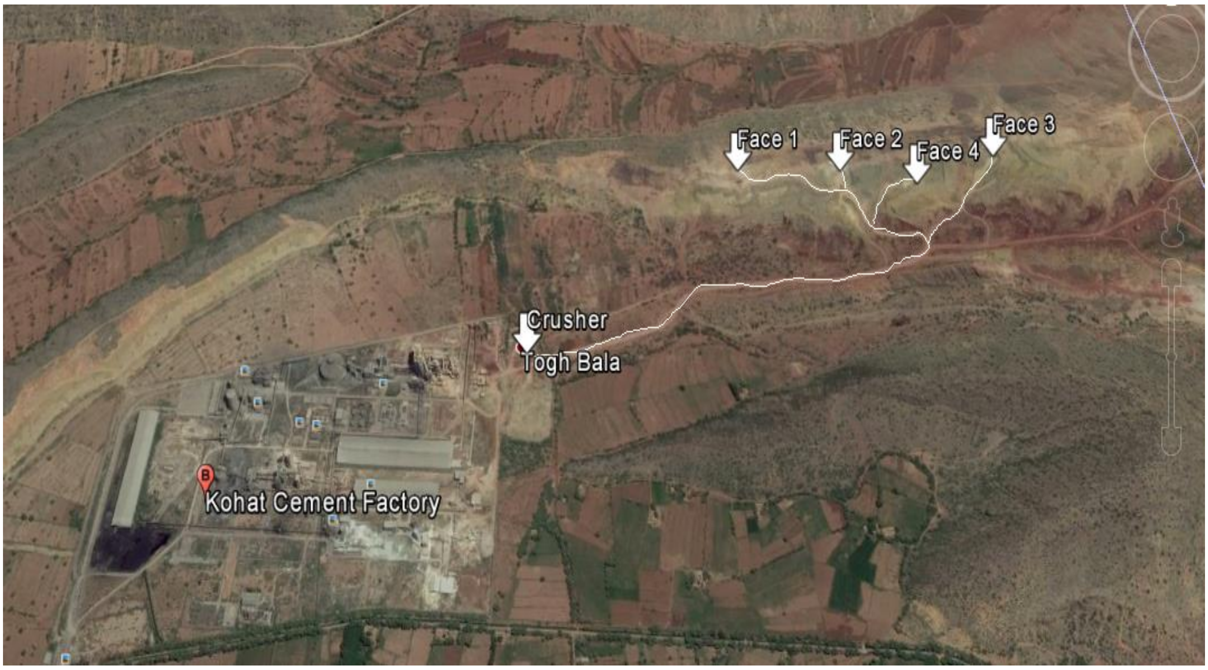

Figure 1. Kohat Cement Factory with location of mining faces and crusher.

The Kohat cement has five quarries, in which, currently, four are in the quarrying operation. This quarry is located about 1500 m from the crusher. The quarries provide not only limestone but also shale up to some extent. Limestone of these quarries varies from low- to high-grade in each quarry. The raw material is handled and transported through the truck/shovel fleet system. The quarry taken as a case study is under the contractor Qadir and Co. The maximum capacity of crusher is about 11000 tons. Qadir and Co is the company that has been dealing with blasting and hauling of the limestone raw material.

6.2. Collected parameters

The raw material hauling system is analyzed for the purpose of minimizing the truck-shovel allocation cost. The required data is collected from the Qadir and Co. The raw material loading and hauling system employs three excavators and eleven trucks. The percent content of the major oxides was found by chemical analysis of limestone for which drill hole samples from different areas of the quarry were collected. The transportation costs for each type of truck from mining faces to the crusher are given in Table 1.

Table 1. Transportation cost ($), truck assign to face, and truck assign to type of shovel.

Truck number	Transportation cost ($) from mining face				Assign to shovel
	Face 1	Face 2	Face 3	Face 4	
1	2.50	2.00	2.30	3.00	2
2	2.50	2.00	2.30	3.00	3
3	2.50	2.00	2.30	3.00	3
4	2.50	2.00	2.30	3.00	2
5	2.50	2.00	2.30	3.00	3
6	2.50	2.00	2.30	3.00	2
7	3.50	2.50	2.80	3.40	1
8	3.50	2.50	2.80	3.40	1
9	3.50	2.50	2.80	3.40	1
10	4.00	3.00	3.20	3.70	1
11	4.00	3.00	3.20	3.70	1

A total of four mining faces are available for the extraction of raw materials. There is an inherent natural variation in the chemical composition of raw materials at the quarry. The limestone quarry is divided into a number of faces, and each face is assigned a quality index in terms of low- and high-grade. Faces 1 and 3 consist of high-grade limestone, while faces 2 and 4 consist of low-grade limestone. Grade of cement raw material at each is given in Table 2. The maximum production capacity of each shovel and availability of each type of shovel is given in Table 3.

Table 2. Grade of material at face.

No. of faces	Material grade (%)		
	1 (SR)	2 (LSF)	3 (AM)
1	1.6	0.65	0.5
2	2.4	0.7	0.5
3	1.3	0.82	2
4	1.01	1.85	0.45

Table 3. Number of shovels with their production capacity and availability.

No. of shovels	Maximum production capacity of shovel (tons)	Availability of shovel
1	450	1
2	300	1
3	300	1

The availability of mining face, cost of moving shovel from one face to another, and availability of raw materials at each face is given in Table 5. The truck capacity, cycle time for each truck carrying raw material from mining face to crusher, and truck compatibility with shovel calculated using Equation 1 is provided in Table 4. In order to achieve the balance of the major oxides, additive shale and laterite are used to combine with limestone. The values of each index at the quarry faces are given in Table 2, which meet the quality requirements by blending with additives. The total shift time is 11 hours and the cost of deviation from target production is taken 2. The truck and shovel allocation problem is solved by the solver kit GUSEK.

Table 4. Number of trucks, cycle time (minutes), compatibility with shovel gives 1 if compatible, if not then its value is 0 and tons of material transported by trucks.

Number of trucks	Cycle time (minutes) of truck from high- and low-grade of material from mining face				Truck compatibility with shovel			Tons of material transported by trucks from face			
	Face 1	Face 2	Face 3	Face 4	Shovel 1	Shovel 2	Shovel 3	Face 1	Face 2	Face 3	Face 4
1	30	29	25	25	0	1	0	20	23	20	23
2	31	29	25	25	0	0	1	20	23	20	23
3	31	29	25	25	0	0	1	20	23	20	23
4	31	29	25	25	0	1	0	20	23	20	23
5	31	29	25	25	0	0	1	20	23	20	23
6	33	29	25	25	0	1	0	20	23	20	23
7	33	32	29	28	1	0	0	27	30	27	30
8	33	32	29	29	1	0	0	27	30	27	30
9	35	33	29	28	1	0	0	27	30	27	30
10	35	36	33	32	1	0	0	32	35	32	35
11	36	36	33	32	1	0	0	32	35	32	35

Table 5. Mining faces, grade of material, shovel moving cost ($), and tons of raw material.

Mining faces	Material quality, 1 for high grade and 0 for low grade	Cost ($) of each shovel moving to mining face			Availability of face; 1 if available, 0 if unavailable	Available material at each face (tons)
		Shovel 1	Shovel 2	Shovel 3		
1	1	4.00	3.20	2.50	1	100,000
2	0	3.00	3.50	4.00	1	140,000
3	1	2.50	2.00	4.50	1	500,000
4	0	1.50	2.30	4.00	1	600,000

7. Results and Discussion

The linear programming formulation addresses the scenario containing 100 integer variables, while the result is generated in less than a minute using the GLPK LP/MIP solver, v. 4.65. The optimal truck-shovel allocation minimizes the total cost to $226.00, while meeting the quality and quantity requirements.

Table 6 presents the optimal production schedule of 11550 tons within the required quality and quantity of limestone raw material at the optimum cost. The results also reveal that shovel 1 is assigned to face 4, shovel 2 is assigned to face 2, shovel 3 is assigned to face 1, and no shovel is assigned to face 3. The time cycle of the trucks allocated to mining faces is given in Table 7.

Table 6. Results of objective function, availability of shovel and face.

Objective function Cost: Z = $226.*00*	Availability	Material limitation	Shovel assign to face
shovel 1	1		Face 4
shovel 2	1		Face 2
shovel 3	1		Face 1
Face 1	1	3300 tons	
Face 2	1	3300 tons	
Face 3	0	0 tons	
Face 4	1	4950 tons	

Table 7. 9(minutes) taken by each type of truck and number of trips.

No. of Trucks	1	2	3	4	5	6	7	8	9	10	11
Total time (minutes)	1980	2640	1320	660	1320	1980	1320	1980	2640	660	660
Number of trips	50	55	35	15	39	57	35	55	69	18	18

The solution to the truck and shovel allocation problem through a cost minimization MILP model including the raw material quality constraints becomes an alternative scientific approach to the resource allocation. The originality of the approach is in the utilization of both the quantity and quality constraints as an input to the model, which leads to an efficient interfacing and synchronization of the quality and quantity plans.

A successful implementation of the optimal resource allocation ensured an approximate average saving cost of about $74 per day (Rs. 11900 @ 1 US Dollar = 161 Pakistani Rupees (source: Universal currency convertor)). As the annual production capacity of cement in Pakistan is about 45.6 million tons during 2019 (source all Pakistan cement association), and on average, 1.5 ton of material is required to produce one ton of cement, therefore, approximately 68.4 million tons of raw materials are required annually. The cost of raw material production can be reduced through improved blending and material handling operations. A potential saving of $433000 per annum can be achieved by the cement industry in Pakistan by implementing the MILP model. The allocation of truck and shovel to various benching according to the quantity and quality requirements maintains that these savings may generally realize since the model always attempts to carry both the quantity and quality constraints simultaneously.

8. Conclusions

The cement manufacturing operations depend greatly upon an accurate allocation of trucks and shovels to mining faces. Therefore, opposed to experience and the trial-and-error approach, the cement industry requires a proven scientific technique for an accurate allocation of truck and shovel to mining faces. For this purpose, the mixed integer linear programming (MILP) model was develop, and to evaluate its results, the case study of Kohat cement quarry to optimize the truck/shovel allocation to the mining faces was taken as a bi-objective function of the followings:

- At optimum cost, provide the required quantity of raw materials.
- At optimum cost, provide the required quality of raw materials.

The analysis of the results obtained, relating the case study, revealed that gains were achievable through employing the MILP model. The results obtained show not only a significant cost reduction but helps in resolving various managerial issues;

- Better coordination among the quarry and quality department
- Better planning related to the required quality and quantity of additives purchased from the market.
- Avoid relocations and frequent movements of mine machinery.

This model considers the quality control of raw materials up to some level; however, it does not consider the production according to the raw material blending requirements. This consideration that may be a linear constraint added to the model.

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مدل‌سازی و بهینه‌سازی تخصیص شاول و کامیون به جبهه‌کارهای معدن در معدن کارخانه سیمان

کوثر سلطان شاه* و صافی اور رحمان

دانشکده مهندسی معدن، دانشگاه مهندسی و تکنولوژی پیشاور، پیشاور، پاکستان

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* نویسنده مسئول مکاتبات: kausarsultanshah@gmail.com

چکیده:

کامیون و شاول دو ابزار اولیه مرسوم برای سیستم ترابری در معادن کارخانه سیمان هستند. یکی از اصلی ترین چالش‌های مرتبط با معادن کارخانه سیمان، تخصیص کارآمد کامیون و شاول به جبهه‌کارهای معدن است. به‌منظور کاهش هزینه‌های عملیاتی کامیون و شاول و با توجه به محدودیت‌های کمی و کیفی، مدل برنامه ریزی خطی عدد صحیح مختلط (MILP) برای تخصیص کامیون و شاول به جبهه‌کارهای معدن کارخانه سیمان ارائه شده است. این مدل با استفاده از ابزار GUSEK بهینه سازی IDE و حل کننده مستقل (GNU Linear Programming Kit) پیاده سازی شده است. مدل MILP در معدن فعال کارخانه سیمان کوهات در کوهات پاکستان اجرا شد. بررسی نتایج حاصل از این مطالعه نشان داد که نتایج قابل توجهی با به کارگیری مدل MILP به دست خواهد آمد. نتایج نه‌تنها نشان دهنده‌ی کاهش قابل توجه هزینه‌ها بود بلکه دردستیابی به هماهنگی بهتر میان بخش معدن و بخش کنترل کیفیت کمک شایانی کرد.

کلمات کلیدی: تخصیص کامیون و شاول، جبهه‌کارهای معدن، بهینه‌سازی، برنامه‌ریزی خطی، معدن کارخانه سیمان.