Optimization of shovel-truck system for surface mining

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Technical Note

Synopsis

In surface mining operations, truck haulage is the largest item in the operating costs, constituting 50 to 60% of the total. In order to reduce this cost, it is necessary to allocate and dispatch the trucks efficiently. This paper describes shovel and truck operation models and optimization approaches for the allocation and dispatching of trucks under various operating conditions. Closed queuing network theory is employed for the allocation of trucks and linear programming for the purpose of truck dispatching to shovels. A case study was applied for the Orhaneli Open Pit Coal Mine in Turkey. This approach would provide the capability of estimating system performance measures (mine throughput, mean number of trucks, mean waiting time, etc.) for planning purposes when the truck fleet is composed of identical trucks. A computational study is presented to show how choosing the optimum number of trucks and optimum dispatching policy affect the cost of moving material in a truck-shovel system.

Keywords: Open pit mine, equipment selection, dispatching, linear programming, closed queuing network theory

Introduction

In a surface mining operation, a materials handling system is composed of loading, hauling and dumping subsystems. Effective and efficient materials handling systems can be developed only through a detailed consideration of these subsystems in a systems analysis framework. The transport of material from production faces to dumping sites is accomplished by rail, truck, belt conveyor or hydraulic transport. Shovel-truck systems are most common in open pit mining. Two available techniques to analyse these systems, linear programming and queuing models, are used and compared in this study. The most important factor in every operation is profitability. Productivity of equipment used is an important factor of profitability. Profitability can be increased by optimization of the equipment combination used. Therefore the first goal in these models is to maximize productivity and hence increase production, which in turn will result in cost reduction.

Studies conducted for the truck allocation were carried out by several authors. Muduli and Yegulalp (1999) studied the modelling truck-shovel systems as a closed queuing network with multiple job classes. Soumis *et al.* (1989) discussed the evaluation of the new truck dispatching in the Mount Wright mine using linear programming. Sgurev *et al.* (2003) studied an automated system for real-time control of the industrial truck haulage in open-pit mines. Alarie and Gamache (2002) studied the overview of solution strategies used in truck dispatching systems for open pit mines. Nenonen *et al.* (1981) used the interactive computer model for truck/shovel operations in an open pit mine; Ramani (1990) studied the haulage system simulation analysis in surface mining. Barnes *et. al.* (1972) studied the probability techniques for analysing open pit production systems. Carmichael (1986) applied cyclic queuing theory to determine the production of open-cut mining operations, and Koenigsberg (1982) used in his study some concepts of queuing theory. Shangyao *et al.* (2008) developed an integrated model that combines ready mixed concrete (RMC) production scheduling and truck dispatching in the same framework. Sabah *et al.* (2003) present a methodology based on the queuing theory, which is incorporated in a computer module to account for the uncertainties that are normally associated with the equipment selection process.

Proposed models

Optimum number of truck assignments to shovels (by employing closed queuing network theory)

In a shovel-truck model, trucks cycle between their assigned shovels and dumps or crushers,

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 Paper received Oct. 2008; revised paper received May 2009.

over haul roads. When calculating cycle time for a truck, the time taken to spot and load, haul, dump and return needs to be considered. The nature of these activities includes variability in the cycle time. Trucks do not normally arrive at the shovel to be 'serviced' in a predictable manner, nor does it take exactly the same time for the shovel to service each truck. The interaction between the randomness of inter-arrival times of trucks and the shovel service time results in either trucks to queling at the shovel or the shovel being idle while waiting for a truck to arrive (Elbrond, 1990).

Ore or waste is moved from shovel locations along a network of haulage roads, to several dumping or crusher stations. Through extensive time studies in the field, data are collected on the load times, the truck travel times, waiting times for the trucks at the shovel and at the dump location, and the truck dump times. Statistical distributions are fitted to the observed data. These distributions permit the random selection of event times for the defined sequence of operations.

The queuing theory calculation is fast and simple. In truck dispatching this could be advantageous because forward estimates of waiting times are important information for the dispatcher. However, most mining applications are highly complex and accurate modelling results in complex queuing models that have no direct analytic solution. Usually, cyclic queuing models are solved by assuming that arrival and service mechanisms are Markovian. Approximation of times of loading hauling and dumping, with exponential distribution is a typical example of this situation.

A typical cyclic queue in an open pit operation may be considered to consist of four phases (Figure1):

1. The shovel (service; loading the trucks)
2. The loaded haulage road (service; travelling loaded)
3. The dump site (service; emptying the trucks)
4. The empty haulage road (service; travelling empty).

Since traveling, loading, waiting and dumping times are exponentially distributed, service rates are the inverse of mean service times. The cycle times of the trucks are calculated as:

The average cycle time = load time + dump time + queuing time at the shovel + queuing time at the dump + loaded haul time + empty haul time.

In the cyclic model the number of possible states for N cycling units (trucks) and M service centres:

$$\binom{N+M-1}{N} = \frac{(N+M-1)!}{(M-1)!N!} \qquad [1]$$

When phase 2 and 4 are transient phases such as travelling phases, the steady state probabilities are solved in terms of one of the unknowns $P(N,0,\ldots,0)$, (Carmichael 1987):

$$P(n_1,n_2,K,n_M) = \frac{\mu_1^{N-n_1}}{\mu_2^{n_2}\mu_3^{n_3}\Lambda\mu_M^{n_M}} P(N,0,K\,0) \qquad [2]$$

$$= \left(\frac{\mu_1}{\mu_1}\right)^{n_1}\left(\frac{\mu_1}{\mu_2}\right)^{n_2}\Lambda\left(\frac{\mu_1}{M_1}\right)^{n_M} P(N,0,K,0) \qquad [3]$$

(n_1, n_2, K, n_M) shows the possible states, which means that there are n_1 units in phase 1, n_2 units in phase 2 and so on. $P(N,0,\ldots,0)$ may be obtained from the requirement that the sum of the probabilities equals 1, such as:

$$\sum P(n_1,n_2,K\,n_M) = 1 \qquad [4]$$

$$P(N,0,\ldots,0) = \left[\sum\left(\frac{\mu_1}{\mu_1}\right)^{n_1}\left(\frac{\mu_1}{\mu_2}\right)^{n_2}\Lambda\left(\frac{\mu_1}{\mu_M}\right)^{n_M}\right]^{-1} \qquad [5]$$

For N cycling units,

$$\sum_{i=1}^{M} n_i = N \qquad [6]$$

N = number of trucks
M = number of phases
μ_i = service rate at i th phase

The probability that a phase is working (phase utilization) is:

$$\Pr[\text{phase } i \text{ is working}] = \eta_i = 1 - \sum P(n_1,n_2,K,n_{i-1},0,n_{i+1},K,n_M) \qquad [7]$$

The expected number of trucks in the queue at the i'th phase is:

$$L_{qi} = \sum n_i P(n_1,n_2,K,n_M) - \sum P(n_1,n_2,K,n_M) \qquad [8]$$

The expected time that a truck spends in the queue at the i'th phase is:

$$W_{qi} = L_{qi}/\Theta \qquad [9]$$

$\Theta = \eta_i\mu_i$; number of trucks being serviced at the i'th phase during one unit of time.

The expected time that a truck spends in the i'th phase is:

$$W_i = W_{qi} + 1/\mu_i \qquad [10]$$

Then average total cycle time for a truck to complete M phases becomes:

$$LCT = \sum_{i=1}^{M}(W_{qi} + \frac{1}{\mu_i}) \qquad [11]$$

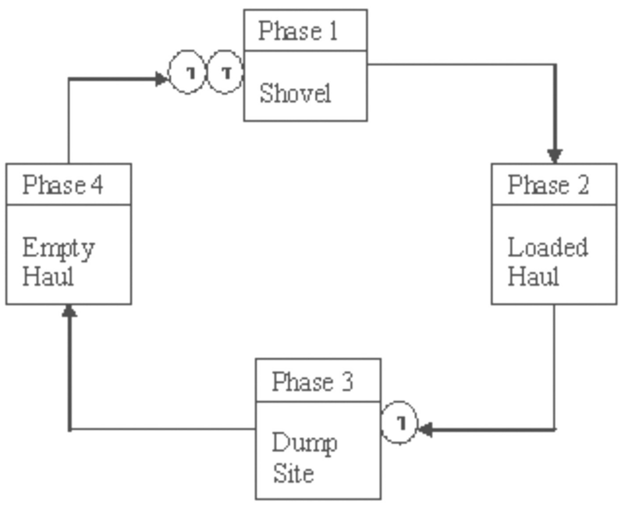

Figure 1—Phases of shovel-truck system

Production over a given time period of interest (typically one shift) can be calculated by the number of loads that trucks take to the dump:

$$\text{Production} = \frac{\text{time period of interest}}{\text{average cycle time}} \times N \times \text{truck capacity} \quad [12]$$

where N is the number of trucks in the system. Also production may be calculated from:

$$\text{Production} = \text{time period of interest} \times \eta_{\text{shovel}} \times \mu_{\text{shovel}} \times \text{truck capacity} \quad [13]$$

η_{shovel} is shovel utilization and μ_{shovel} is shovel loading rate.

For shovel-truck type operations, the minimum unit cost of moved material is the main concern. When the cost is of prime importance, a trade-off is sought between the cost of idle time of the shovel and the cost of providing extra trucks. The solution yields the optimum number of trucks of any given capacity that can be assigned to a shovel.

For an operation involving single shovel and N trucks, the total hourly cost is $C_1 + C_2 N$, where C_1 is the cost per unit time of shovel and C_2 is the cost per unit time of a truck. Both costs include ownership and operating costs. So the total cost for unit production can be found from:

$$C = \frac{C_1 + C_2 N}{\text{unit production} \times \text{truck capacity}} \quad [14]$$

Once the unit production cost is found for a different number of trucks, the cost can be plotted vs. the number of trucks, and the optimum truck number, which minimizes the cost, can easily be determined.

Dispatching of trucks to shovels (by linear programming)

The linear programming model assumes no truck queuing under ideal conditions and guarantees maximum shovel utilization. LP model minimizes the number of trucks required for shovel coverage without truck queuing and is equivalent to maximizing overall production rate. The LP function to be minimized is the total number of trucks required to maintain all rate-limiting nodes at their maximum production rate, subject to continuity, rate limiting, and non-negativity constraints. A pit is viewed as a fixed number of sources (load points) and sinks (dump points), called nodes, connected by valid transaction routes called paths. Shovels dump sites, and crushers are the nodes in an LP model. Roads are the paths between nodes. Some nodes are considered rate limiting (shovels), whereas others (waste dumps) are assumed capable of handling all transactions.

If there are N nodes in a pit, then there are $N^*(N-1)$ directional paths interconnecting these nodes, although some paths may not used under normal operating conditions. For example, dump-to-dump and shovel-to-shovel are never used. Also some shovel-to-dump paths may not be feasible because of topography or non-existing roads, and not used.

The general problem of allocating resources (trucks) to activities (node transactions) can be formulated as follows: (White *et al.* 1982)

$$\text{Minimize}: NT = SUM(I = 1; NP) \text{ of } PI * TI + SUM(J = 1; NS) \text{ of } PJ * SJ + NO \quad [15]$$

The objective function minimizes the number of trucks on the road + number of trucks at shovels (source points) + number of trucks at dump sites (sink points).

Subject to the constraints of continuity:

$$SUM(NODEI\ OUTPUTS) = 0 \quad [16]$$

This means balancing equations at each node such as:

incomings-outgoings = 0

and limiting rates at sources:

$$SUM(LIMITING\ NODEI\ OUTPUTS) - RI = 0 \quad [16]$$

Meaning; Σoutgoings=1/loading time

and, finally, non-negativity constraints:

PI ≥ 0

where:

NT = performance functional (number of trucks)
NP = number of feasible paths
NS = number of non-rate-limiting sinks
NO = number of rate-limiting nodes
PI = average rate over path i (trucks/min)
TI = average travel time over path i (min)
PJ = sum of all sink input rates (trucks/min)
SJ = average sink processing time (min)
RI = limiting node rate (trucks/min)

The LP solution yields the desired path capacities in trucks/ unit time for each valid path.

Case study

Mine information

In this case study, some research has been carried out to optimize the material handling system for overburden removal of an open-pit coal mine. The coal mine is situated about 65 km north of Bursa, in western Turkey, and has been in continuous operation since 1979. Currently, the mine supplies coal to Orhaneli power plant unit (1 × 210 MW) and to domestic users. In this case, the overall measurements of the mine should be designed again in terms of transporting system, equipment fleet, etc. Some technical parameters of the working site, which affect the system, have been researched thoroughly and summarized below in detail (Bascetin 2002; Bascetin 2004):

The present extent of the open pit is 5 500 m by 3750 m and a total of 75 m of overburden removed in three 15 m high mine benches. The face inclination on individual benches is 75 degrees, while overall pit slope is 45 degrees. The mine will be worked over 18 years at the rate of one shift (12 h) per day, seven days a week for 300 days per year, and the scheduled operating time is 3600 h/year. The equipment in the inventory reported are given, briefly, in Table I.

Optimization study

The overburden removal subsystem is analysed for the purpose of minimizing the truck fleet size and the minimizing unit cost composed of loading and hauling. The overburden removal subsystem employs two 15 yd^3 and two 10 yd^3 shovels both with 77 ton trucks. The mine has two dumping sites. The shovel truck system requires about 9 million m^3 overburden removal yearly. The remaining 6 million m^3 is handled by dragline. The present operation of the shovel truck system, is a closed system as shown in Figure 2.

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Table I

Equipment on the mine

Equipment	Number	Explanation
Drilling units	3	9'' DM50
Rope shovels	2	Marion 191 MII -11,4 m^3 (15 yd^3)buckets (2 in waste)
Front shovels	5	PH 1900 AL-7.64 m^3 (10 yd^3) buckets (4—currently 2 in waste and 1 in ore)
Dragline	1	1260-W Bucyrus-Erie-25 m^3 bucket
Trucks	50	Caterpillar 777-77 tonnes—(27) Komatsu 785-2, 77 tonnes—(13) Komatsu 785-2, 50 tonnes—(4) Komatsu HD 465-3—(6, coal trucks)
Bulldozer	9	Komatsu D355A-410 hp—(5) Caterpillar 81—(3) Cat 824 wheeled dozer—(1)
Loader	7	Caterpillar front-end loader—(4) Volvo front-end loader with 5.5–6 m^3 buckets—(1) Champion-120 hp-(2)
Grader	1	Caterpillar—(275 hp)

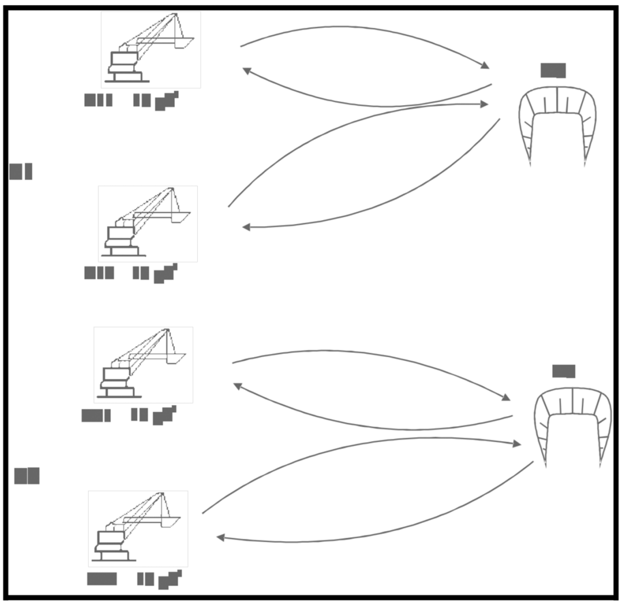

Figure 2—Shovel-truck system as closed system

In order to optimize the shovel truck system, two aspects are considered in order.

➤ Optimum number of truck assignments to shovels (by employing closed queuing network theory)

➤ Dispatching of trucks to shovels (by linear programming).

Optimum number of truck assignments to shovels

All possible paths are analysed by the closed queuing network model, which is explained earlier. Path lengths and travelling times are shown at Table II. For this purpose all possible truck paths to shovels are shown in Figure 3.

Manoeuvering + loading times of the 77 tons trucks are 2.03 and 3.0 minutes for 15 yd^3 and 10 yd^3 shovels respectively. Truck emptying time at waste site is 1.5 minutes. The cost of the shovels and trucks is given in Table III.

An example of queuing calculations, from shovel S22 to dump site H6, is given below for 4 trucks allocated to the shovel. There area total of 35 states, and corresponding state probabilities are given in Table IV.

Using Table IV, system performance measures can be calculated.

Utilization of the shovel,

$$\eta_1 = 1 - \sum P(0, n_2, n_3, n_4)$$
$$= 1 - \sum(\text{state } 1, 2, 3, 5, 6, 8, 11, 12, 14, 17, 21, 22, 24, 27, 31 \text{ possibilities})$$
$$= 1 - 0.384$$
$$= 0.616$$

Table II

Lengths and travelling times for possible paths

Path	Path length (m)	Travel loaded (min)	Travel empty (min)
S11-W5	780	2.5	1.5
S11-W6	1205	5.4	3.9
S12-W5	2615	6.5	4.6
S12-W6	1068	4.7	3.0
S21-W5	1500	6.0	4.6
S21-W6	1874	8.0	5.3
S22-W5	1337	5.7	4.2
S22-W6	1753	7.5	5.0

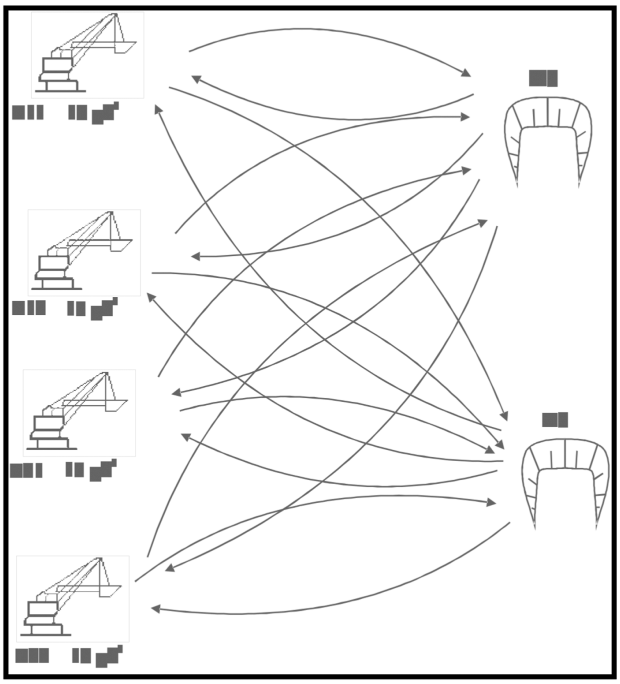

Figure 3—All possible truck paths

Table III

Cost of shovels and trucks

Equipment	Ownership cost $/h	Operating cost $/h	Total cost $/h
15 yd^3 shovel	25.33	100.00	125.33
10 yd^3 shovel	22.67	85.00	107.67
77 ton truck	16.67	40.00	56.67

Table IV

System states and corresponding probabilities

State no.	System state	Coefficient	Prob. (state)
1	0 0 0 4	.321502	.005784
2	0 0 1 3	.385803	.006941
3	0 1 0 3	1.929013	.034704
4	1 0 0 3	.771605	.013882
5	0 0 2 2	.347222	.006247
6	0 1 1 2	1.736111	.031234
7	1 0 1 2	.694444	.012494
8	0 2 0 2	4.340279	.078085
9	1 1 0 2	3.472223	.062468
10	2 0 0 2	1.388889	.024987
11	0 0 3 1	.208333	.003748
12	0 1 2 1	1.041667	.018740
13	1 0 2 1	.416667	.007496
14	0 2 1 1	2.604167	.046851
15	1 1 1 1	2.083333	.037481
16	2 0 1 1	.833333	.014992
17	0 3 0 1	4.340279	.078085
18	1 2 0 1	5.208334	.093702
19	2 1 0 1	4.166667	.074961
20	3 0 0 1	1.666667	.029985
21	0 0 4 0	.062500	.001124
22	0 1 3 0	.312500	.005622
23	1 0 3 0	.125000	.002249
24	0 2 2 0	.781250	.014055
25	1 1 2 0	.625000	.011244
26	2 0 2 0	.250000	.004498
27	0 3 1 0	1.302084	.023425
28	1 2 1 0	1.562500	.028111
29	2 1 1 0	1.250000	.022488
30	3 0 1 0	.500000	.008995
31	0 4 0 0	1.627605	.029282
32	1 3 0 0	2.604167	.046851
33	2 2 0 0	3.125000	.056221
34	3 1 0 0	2.500000	.044977
35	4 0 0 0	1.000000	.017991
Total		55.584150	1.000000

The output from phase 1 = $\Theta_1 = \eta_1, \mu_1 = 0.616 \times 0.3333$
= 0.205 trucks/min

L_{q1} = average number of trucks waiting in the queue at the shovel,
= 1 x $\sum$ (state 10, 16, 19, 26, 29, 33 probabilities)
+ 2 x $\sum$ (state 20, 30, 34 probabilities)
+ 3 x $\sum$ (state 35 probability)
= 0.42 trucks

L_{q3} = average number of trucks waiting in the queue at the dump,
= 1 x $\sum$ (state 5, 12, 13, 24, 25, 26 probabilities)
+ 2 x $\sum$ (state 11, 22, 23 probabilities)
+ 3 x $\sum$ (state 21 probability)
= 0.09 trucks

W_{q1} = average waiting time in the queue at the loader,
= L_{q1}/Θ = 2.045 min

W_{q3} = average waiting time in the queue at the dump,
= L_{q31}/Θ = 0.433 min

$$\text{Total cycle time} = \frac{1}{\mu_1} + \frac{1}{\mu_2} + \frac{1}{\mu_3} + \frac{1}{\mu_4} + W_{q1} + W_{q3}$$
= 19.478 minutes

Production = 17.453 tons/minute

$$\text{Unit cost} = \frac{C_1 C_2 N}{\text{unit production x truck capacity}} = 31.93¢ \text{ tonne}$$

The above calculations are carried out for 2,3,...,6 trucks and results obtained are summarized in Table V, and cost per ton vs. number of trucks is plotted in Figure 4.

The results of the queuing network solution to determine the optimum truck number, which minimizes the unit cost hauled for all possible paths along with shovel utilization and production are found in Table VI.

As seen from Table VI, from S11 (shovel 11) to W5 (waste 5) with 3 trucks, from S12 to W6 with 5 trucks, from S21 to W5 with 6 trucks and from S22 to W5 with 4 trucks result in the lowest cost employing 18 trucks in total.

Dispatching of trucks to shovels

Figure 3 shows all possible feasible paths for Orhaneli open-pit mine for overburden removal. In Figure 3, trucks are free to travel between shovels and waste sites. They are not assigned to a single shovel. In this way, after a truck dumps its load, it may travel to any shovel for the next load. LP

Table V

Summary of system measures from shovel S22 to dump site H6

Number of trucks	Waiting time (min)		Shovel utilization	Production (tons/min)	Unit cost (¢/ton)
	shovel	dump			
2	0.529	0.132	0.339	9.624	38.27
3	1.199	0.277	0.487	13.799	33.54
4	2.045	0.433	0.616	17.453	31.93
5	3.108	0.595	0.724	20.706	31.47
6	4.426	0.759	0.811	22.187	33.63

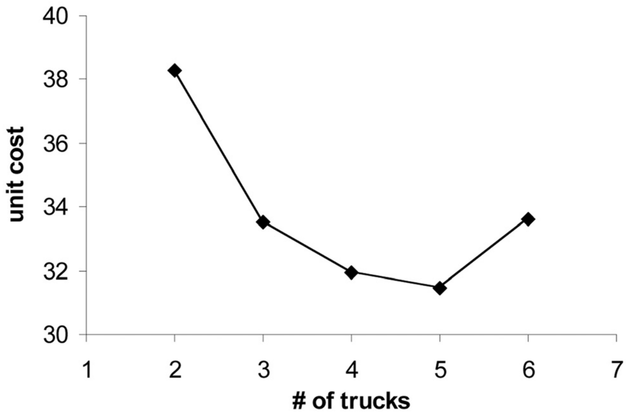

Figure 4—Unit cost vs. number of trucks

Table VI

Optimum truck solution

Path	Optimum truck fleet size	Waiting time(min)		Utilization of shovel	Production tons/min	Unit cost cents/ton
		At shovel	At waste			
S11-W5	3	2.48	0.54	0.781	22.137	20.91 **
S11-W6	4	2.59	0.53	0.709	20.095	27.73
S12-W5	6	2.15	0.99	0.686	28.683	27.04
S12-W6	5	2.09	0.99	0.785	29.69	22.94 **
S21-W5	6	2.24	1.03	0.701	29.292	26.48 **
S21-W6	6	1.81	0.86	0.625	26.157	29.65
S22-W5	4	2.47	0.51	0.690	19.563	28.48 **
S22-W6	5	3.11	0.59	0.724	20.706	31.47

formulation determines the optimal path for trucks to follow. We assume that path to follow for a truck does not change in time, as in real time dispatching.

If we call X_{ij} the average number of trucks per minute over path *i-j* at an instant snapshot of the system, path variables are as shown in Table VII.

The following LP formulation determines the optimal routes for trucks.

The objective function minimizes the total number of trucks, the number of trucks on the road, the number of trucks at the shovels, and the number of trucks at waste dumps. Such as:

Min Z = number of trucks on the road * travelling time over that path +
number of truck at sink points (incoming) * duration at that point + number of trucks at source points (shovels)

MIN = 2.5*X15+1.5*X51+5.4*X16+3.9*X61+6.5*X25+4.6*X52+4.7*X26+3.0*X62+6.0*X35+4.6*X53+8.0*X36+5.3*X63+5.7*X45+4.2*X54+7.5*X46+5.0*X64+1.5*X15+1.5*X25+1.5*X35+1.5*X45+1.5*X16+1.5*X26+1.5*X36+1.5*X46+4;

Subject to:

Balancing equations at each node (incoming-outgoing = 0);

X51+X61–X15–X16 = 0;
X52+X62–X25–X26 = 0;
X53+X63–X35–X36 = 0;
X54+X64–X45–X46 = 0;
X15+X25+X35+X45–X51–X52–X53–X54 = 0;
X16+X26+X36+X46–X61–X62–X63–X64 = 0;

Limiting rates at sources (truck rates being processed at source points, i.e. ∑outgoing = 1/loading time):

X15+X16 = 1/3;
X25+X26 = 1/2.033;
X35+X36 = 1/2.033;
X45+X46 = 1/3;

Nonnegativity constraints;
(X15,X51,X16,X61,X25,X52,X26,X62,X35,X53,X36,X63,X45,X54,X46,X64)>=0

The result of the above LP formulation (Table VIII) shows that the optimum path for trucks should be such that nonzero values and path capacities are in trucks/min for each valid path. Figure 6 illustrates the optimum paths as determined by the LP model for a given set of travel times and shovel loading times. The optimal paths are: from S11 (shovel 11) to W5 (waste 5), from S12 to W6, from S21 to W5 and from S22 to W5. This result is in close agreement with the queuing network solution. Figure 5 shows the optimal dispatching paths. When one examines the optimal paths, they are the same paths which queuing solution results with minimum loading and hauling costs.

The optimizing study for Orhaneli open pit mine results in producing about 10.1 million m^3 overburden removal in a year with 4 shovels (2 units of 15 yd^3 and 2 units of 10 yd^3) and 18 units of 77 tons trucks (which is the objective function value) over the required minimum 9 million m^3 yearly overburden removal. This analysis does not include equipment breakdown. The average cost of hauling is 19.07 ¢/m^3

Table VII

Path variables for LP modelling

Path	Path variable	Path	Path variable
S11-W5	X15	W5-S11	X51
S11-W6	X16	W6-S11	X61
S12-W5	X25	W5-S12	X52
S12-W6	X26	W6-S12	X62
S21-W5	X35	W5-S21	X53
S21-W6	X36	W6-S21	X63
S22-W5	X45	W5-S22	X54
S22-W6	X46	W6-S22	X64

Table VIII

Result of LP problem

Variable	Value
X15	0.3333
X16	0.0000
X25	0.0000
X26	0.4918
X35	0.4918
X36	0.0000
X45	0.3333
X46	0.0000
X51	0.3333
X61	0.0000
X52	0.0000
X62	0.4918
X53	0.4918
X63	0.0000
X54	0.3333
X64	0.0000

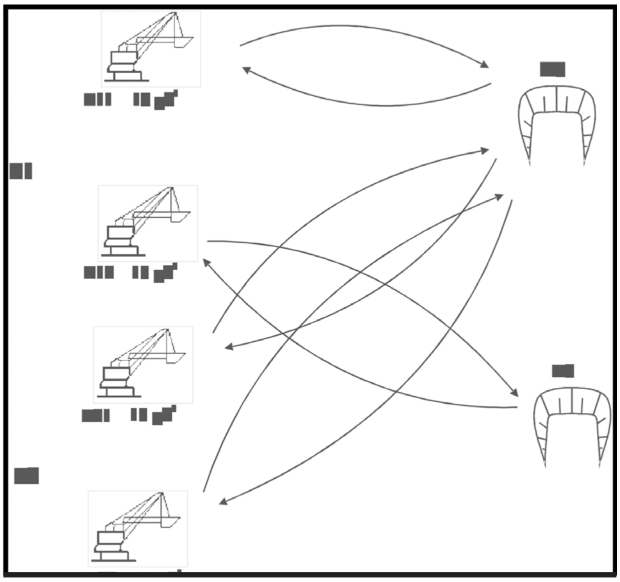

Figure 5—Optimum truck routes for dispatching

Total production = 100.682 tons/min
= 50x100.682 = 5034 tons /h
(assuming 50 minutes work per hour)
= 12x5034 = 60,408 tons/day (12h per working day)
= 300x60,408=18 122 400 tons/year
(300 working days per year)
= 14,048 372 m^3/year (loose)
= 10 106 743 m^3/year (in place)

Average cost = 24.60 ¢/ton or 19.07 ¢/m^3

Conclusion

The methodologies developed and presented in this paper have the potential to be useful for mine operators for loading and haulage planning in open pit mines and/or at the stage of equipment procurement. Since the cost of shovels and trucks is several hundred dollars per hour, the application of the methodologies has potential for substantial savings. The methodologies developed have been validated for a range of shovels and off-highway dump trucks. The process has proven the applicability of the theoretical model proposed by the authors.

The first stage consisted of determining of the optimal number of trucks working with each shovel in the system using a model based on the closed queuing network theory. A complete example has been provided for shovels working with identical trucks. The results clearly demonstrate the applicability of such an approach for the issues under study. As a result of the queuing network solution, the optimum truck number, which minimizes the unit cost hauled for possible paths along with shovel utilization and production/minute ise found to be: from S11 (shovel 11) to W5 (waste 5) with 3 trucks, from S12 to W6 with 5 trucks, from S21 to W5 with 6 trucks and from S22 to W5 with 4 trucks, which result in lower costs using 18 trucks in total.

At the next stage, it has been determined how the trucks should be dispatched to shovels, using the LP model. Results obtained are interesting and applicable to planning loading and haulage operations in open pit mines or at the procurement stage of the equipment. The optimal route of trucks for Orhaneli coal mine is: from S11 (shovel 11) to W5 (waste 5), from S12 to W6, from S21 to W5 and from S22 to W5. This result is in close agreement with the queuing network solution, which provided the minimum loading and hauling costs.

Acknowledgements

This work was supported by the Research Fund of Istanbul University. Project number: 62/23012003 and UDP-887/05122006.

Appendixes

List of symbols

N	number of cycling units (trucks)
M	number of service centers
μ_I	service rate at i th phase
L_{qi}	expected number of trucks
Θ	number of trucks being serviced at the i'th phase during one unit time
W_i	expected time that a truck spends in the i'th phase
C_1	cost per unit time of shovel
C_2	cost per unit time of a truck
C	total cost for unit production

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