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AN OPTIMIZING MODEL TO MATCH MINING EQUIPMENT SETS

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I. Introduction

Surface mining is a complex materials handling problem that involves the task of removing and replacing different overburden strata and loading and hauling coal in a specific order. Miners have large capital investments in primary strippers, bulldozers, scrapers, loaders, and haulers. Excess capacity of any unit results in higher investment than necessary and fixed costs for which the miner receives no return; but heavy penalties may be assessed against under-capacity if the miner fails to produce to the level of contractual commitments. The miner's objective, then, should be to assemble an equipment fleet that meets the desired level of production at the least cost without significant deviation from required capacity. For example, in a dragline or stripping shovel operation where the primary stripper is the major investment component, adequate support equipment must be available to keep the primary stripper working at full capacity. If scrapers are used as primary strippers, the number of pushers must be matched to the number of scrapers.

The purpose of this paper is to illustrate the capabilities of an analytical model developed to calculate the production capacity and the costs of various combinations of coal-mining machinery. The model matches the numbers of each type of machine resulting in the least cost machine combination. First, a conceptual framework for cost calculations and machine matching is developed and illustrated. Next the costs of operating various loader-truck combinations at a given level of production are evaluated. Finally, various examples are used to illustrate how the interaction of costs and production levels determine the least cost combination of different sizes and types of machines under various job situations.

II. METHODOLOGY

The optimal machinery complement is achieved by selecting that combination which provides the desired production under the most prevalent mining conditions at the least cost, yet still has the capability to maintain production under the most adverse conditions encountered. To choose an optimal machinery complement, the miner must first determine the order in which mining tasks are to be performed based on topography, overburden characteristics, and the mining plan. Desired annual production, often obtained from contractual commitments, determines total volume of material to be moved. Types and sizes of equipment in the miner's opportunity set depend on mining conditions, his financial situation, and availability of new or used equipment.

Hourly machine production is determined from cycle time and production per cycle which is affected by machinery size and overburden characteristics such as type of strata, hardness, swell factor, and bucket fill factor. Cycle time for mobile units is determined from grades, length of haul, rolling resistance, machine availability, job efficiency and acceleration characteristics of the machine.

Mining costs depend on hourly production, machine costs per hour, and investment. The specific mining costs attributable to machinery include owning costs (depreciation, interest, taxes, and insurance) and operating costs (fuel, labor, lubricants, maintenance and replacement items). Dividing total cost per hour by expected production per hour gives cost per unit of production. Figure 1 shows the information required, machine selection process flow, cost calculation, and output information used in the selection of equipment for a mine. A complete discussion of expected production per hour and cost per ton calculations for machines operating independently is included in Otte and Boehlje (10). This paper discusses how the most efficient and hence least cost machine combinations are calculated once other cost and production coefficients have been determined.

Mining tasks such as loading and hauling coal or push-loading scrapers require two different types of machines, i.e. loaders and trucks or scrapers and bulldozers. The total amount of production that can be obtained depends on the interaction efficiency of machines as well as hourly production capacity of each machine. When machines, and thus production capacity, come in large lumps for each unit added, the interaction of combinations becomes important in the selection process. For instance, with loader-truck combinations, the machine interaction efficiency changes with the absolute size or the relative proportion of each in the combination because of machine interference and wait time.[1] The relative proportion of each machine in the combination influences both total production and the efficiency of the machines. The relationship between relative proportion of individual units and their operating cycle time results in a specific match ratio which is calculated from the number and cycle time of each type of machine. The match ratio provides a method for determining the interaction efficiency of different machinery combinations and is determined as follows:

$$(1) \quad M = \frac{N_i \; S_j}{N_j \; S_i}$$

where:

M = match ratio

N_i = number of machine type i

S_j = cycle time for machine type j

N_j = number of machine type j

S_i = cycle time for machine type i

The match ratio relates the interaction efficiency of one type of machine to another type of machine for various machine combinations. Figure 2 shows the relationship between match ratio and interaction efficiency for coal loaders and haulers. The two linear segments represent the theoretical interaction efficiency. A match ratio of one (1) results in the optimal interaction efficiency for the machine combination.

A discussion of several points on Figure 2 should clarify the relationship among match ratio, interaction efficiency, and production. Point A represents a combination of one loader filling ten trucks. Assume the truck cycle time is ten minutes and the time required by the loader to fill the truck is two minutes. This combination has a match ratio of two (2). The loader is fully employed but the trucks are under-utilized. The efficiency for the loader is high because it is fully employed, but the combination is expensive because the trucks have a large amount of wait time. Adding another loader gives a match ratio of one (1) illustrated by point B on the theoretical interaction efficiency curve. This combination has a 100 percent loader interaction efficiency, resulting in twice as much production, maximum truck utilization and a lower unit cost than point A.

There is a limit on the number of loaders that can be added and still increase production. With a specified amount of truck hauling capacity, adding loaders will eventually result in interaction efficiencies of less than one which reduces the efficiency of all loaders. Point C on Figure 1 shows the efficiency of four

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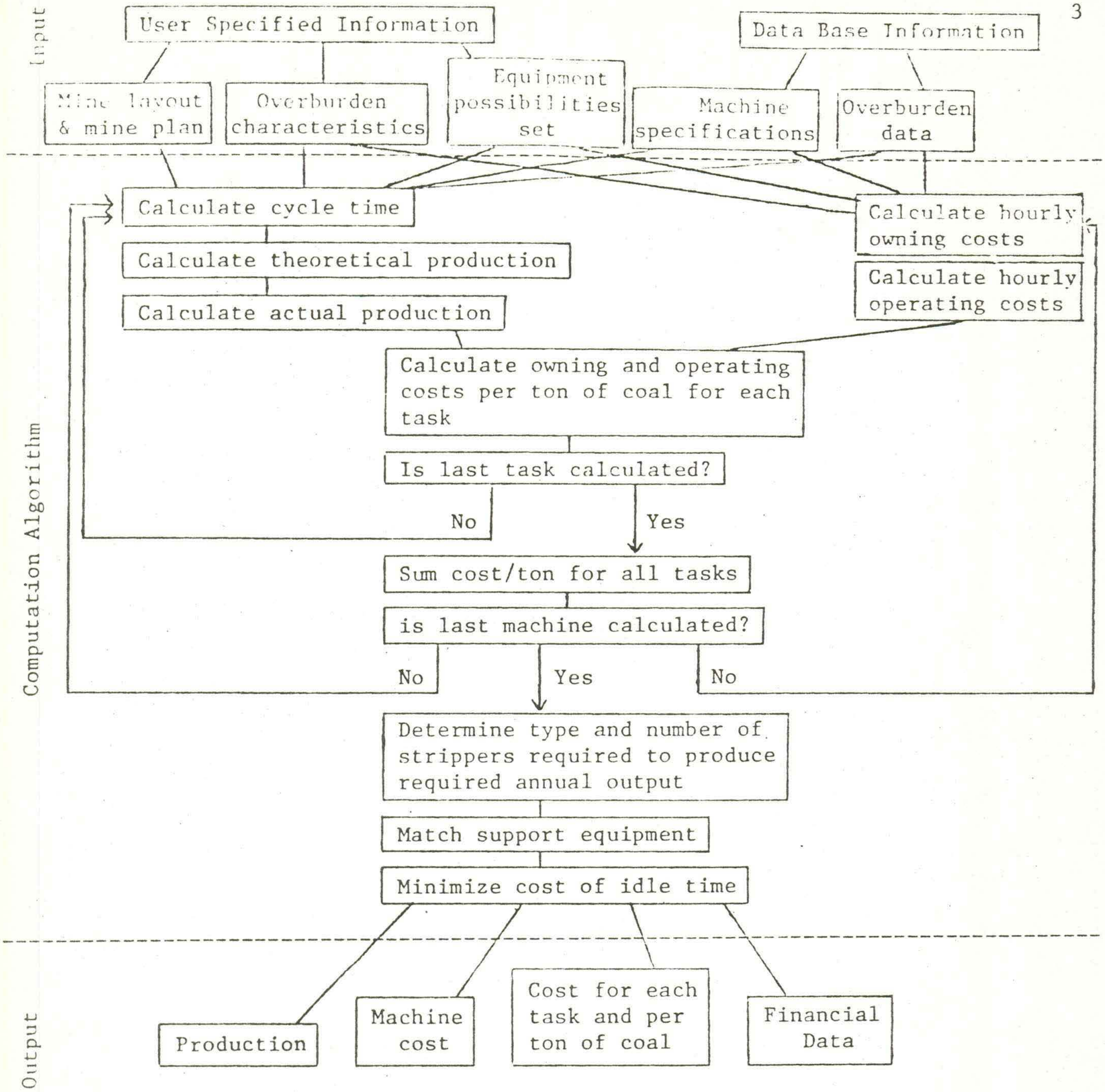
[1] The interaction efficiency changes and production fluctuations are non-linear as additional units are added in a combination.

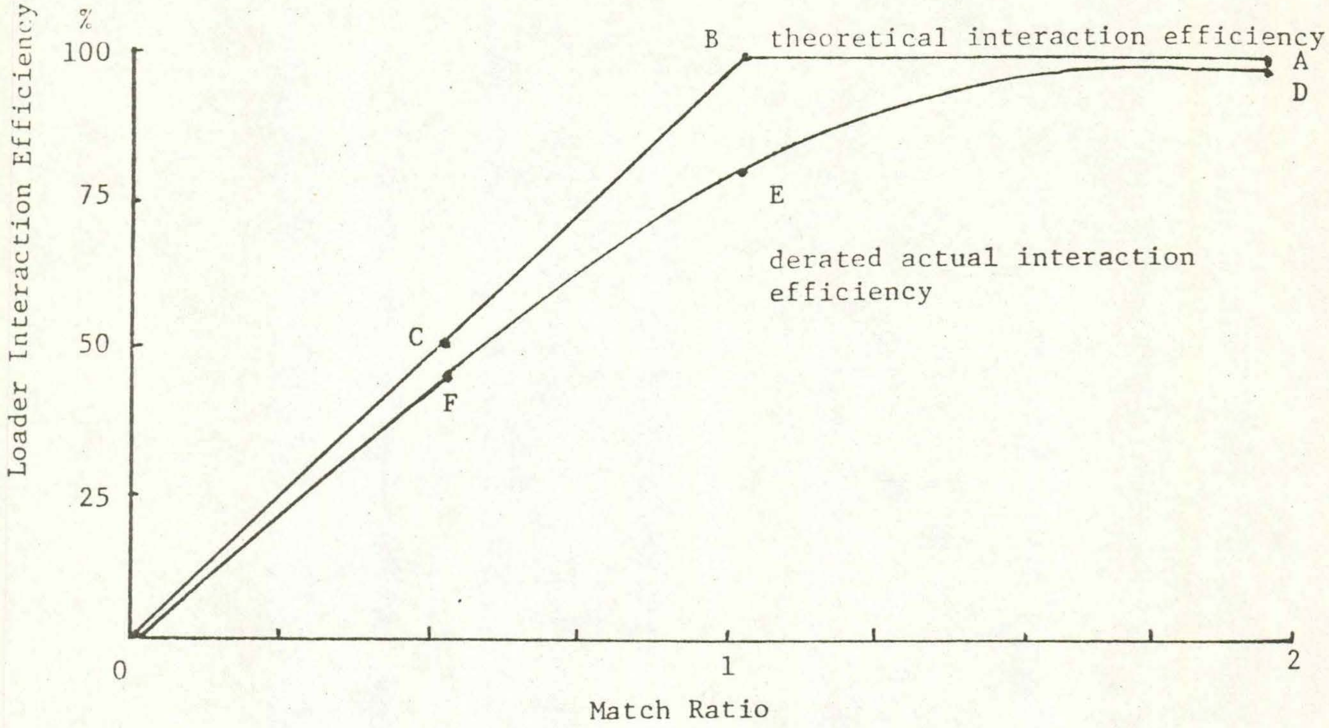
Figure 1. Process Flow Diagram



loaders and ten trucks. The theoretical interaction efficiency is 50 percent, so the four loaders only load half their theoretical capacity. The trucks are fully utilized, but the total cost is higher than point B, because more loaders are employed.

Because of traffic congestion and other vehicle interference which lengthens the cycle time, the theoretical interaction efficiency is never obtained under actual mining conditions; consequently, theoretical interaction efficiency must be derated. Over an extended period, the time lost (wait time) due to these random fluctuations for each machine combination (match ratio) falls into a normal distribution. The mean of the wait time distribution can be determined for each match ratio, and this mean is then subtracted from the theoretical interaction efficiency for each combination. The result is the derated actual interaction

Figure 2. Interaction efficiencies resulting from various combinations of loaders and haulers determined by match ratio



efficiency curve also shown in Figure 2.

Each match ratio identifies a point on the actual interaction efficiency curve, and this efficiency is then used in the actual production calculations. The relationships among match ratio, actual interaction efficiency and production for points D, E, and F on the derated actual interaction efficiency curve are similar to the relationships for points A, B, and C on the theoretical interaction efficiency curve discussed above. The loader is used as a base in this example (and in Figure 1) because maximum production capability depends on its capacity to load coal to be hauled away from the mine. Similar curves can be developed for haulers and are used when hauling capacity is the most limiting operation in a process requiring combinations of machines (e. g. dozers push loading scrapers).

Expected hourly production is calculated from the actual interaction efficiency as:

$$(2)\ P_{ik} = A_i N_{ik} E_{ik}$$

where:

P_{ik} = expected hourly production for machine i (load or haul) in combination k

A_i = actual production capability of machine type i working without other vehicle interference

N_{ik} = number of machines of type i in combination k

E_{ik} = interaction efficiency of machine i working in combination k

Once the expected hourly combination production is calculated, the number of hours the combination will be required to work to meet contract requirements is determined as:

(3) $H_k = J/P_{ik}$

where:

H_k = annual working hours required for combination k

J = annual mine output desired

Since high cost penalties occur if machines have excess capacity, the existence of excess capacity must be determined:

(4) $R_n = \frac{J}{M}$

where:

R_n = combination hourly production which would give desired annual output without overtime or excess capacity

M = number of working hours per year in number of shifts designated by the miner

If $P_{ik} > R_n$, machine combination k has excess capacity.

Owning and operating costs for a particular machine combination are calculated as:

(5) $T_k = \sum_i N_{ik} C_{ik}$

where:

T_k = total owning the operating cost per hour for all machines in combination k

N_{ik} = number of units of machine i in combination k

C_{ik} = owning and operating cost per hour for one unit of machine i in combination k

(6) If $H_k \leq M$, then $C_{ik} = U_i + L_i + B_i$

(7) If $H_k > M$, then $C_{ik} = U_i + L_i + B_i + \left[\frac{H_k - M}{H_k} (L_i + D_i) Q_i \right]$

U_i is the owning and operating costs per hour for one unit of machine i without labor costs

L_i is the hourly labor wage of machine i operator

B_i is the labor benefits paid to machine i operator (B_i = f (hours, tons))

D_i is the labor wage differential among shifts for machine i operators

Q_i is the overtime labor wage differential for machine i operators

$\frac{H_k - M}{H_k}$ denotes the fraction of overtime hours

After the total costs are calculated, the cost/ton of production is calculated as in equations (8) or (9)

$$(8)\ \text{If } P_{ik} \leq R_n,\ \text{then } K_t = T_k/P_{ik}$$

$$(9)\ \text{If } P_{ik} > R_n,\ \text{then } K_t = T_k/R_n$$

where:

K_t = cost per ton of production

Equation (9) penalizes excess capacity by spreading the higher costs associated with higher potential productive capability over the lower rate of production.[2]

III. MATCHING LOADERS AND TRUCKS

The following tables illustrate how the matching program is used to select the optimal number of wheel tractor loaders and off highway trucks to load and haul two million tons of coal annually. Alternative sizes and types of loaders and trucks will be included in the analysis in both single and double shift operations.

As currently structured, the computer model calculates cost per unit of production for combinations including up to 25 hauling units and 10 loading units. Table 1 shows data generated for selected combinations of 3 cubic yard loaders loading 36 cubic year trucks which haul coal from the pit in one shift per day. A single shift has 1813 operating hours per year, requiring minimum capacity of 1103 tons per hour to remove the annual production of 2 million tons from the pit. Combinations in Table 1 with hourly production less than 1103 tons per hour must work overtime, while combinations with production capacity greater than 1103 tons per hour have excess capacity. The total cost is the sum of owning and operating costs per hour for all loaders and trucks, and reflects the cost of all applicable overtime. For example, using the combination of 7 trucks and 4 loaders, the normal shift owning and operating cost would be $652.16 per hour. (7 trucks x $64.36/truck/1 hour) + (4 loaders x $50.41/loader/hour). The $48.22 per hour cost differential between $652.16/hour and $700.38/hour shown in Table 1 represents the increase in average total hourly machine cost resulting from higher hourly cost for overtime operation.

Table 1. Match Ratio, Cost and Production, and Cost Per Unit of Production for Different Combinations of 3-Cubic Yard Loaders and 36-Cubic Yard Trucks Loading 2 Million Tons of Coal Annually in One Shift.

Number of Trucks	Number of Loaders	Match ratio	Combination Owning and Operating Cost ($/hr)	Production (BCY or T/hr)	Cost per Ton ($/T)
7	4	0.92	700.38	939.4	0.746
8	4	1.06	756.82	1030.3	0.736
9	4	1.19	814.80	1109.3	0.738
7	5	0.74	748.55	987.5	0.758
8	5	0.85	802.04	1099.4	0.730
9	5	0.95	861.15	1199.2	0.780
7	6	0.62	798.08	1016.0	0.786
8	6	0.70	848.94	1136.7	0.769
9	6	0.79	913.26	1257.5	0.828

[2] Since the owning costs are calculated per operating hour, a higher capacity combination can achieve production with less hours of operation; therefore, the excess capacity penalty is slightly understated using standard accounting practices.

The costs in Table 1 are calculated by first determining hours of overtime operation required. Overtime labor and benefits costs are calculated by multiplying the overtime charge by the number of units by the hours of overtime for each unit. Total non-overtime operating costs and total overtime operating costs are then added to determine total cost to attain the desired production for a given machinery set. This total is then divided by the hourly production to obtain the costs per ton shown in Table 1.

In combinations with excess capacity, the non-overtime shift hourly cost for each unit is used to calculate total owning and operating cost because no overtime must be worked; consequently, total costs are divided by 1103 tons per hour (production required per hour to meet contract output) rather than the actual production capacity which increases cost per ton.

In Table 1, the combination of 8 trucks and 5 loaders has the lowest cost per unit of output, but must work 6 hours of overtime to achieve the desired production. The combination of 9 trucks and 5 loaders would have a cost of $0.718 per ton if it worked at its capacity of 1199.2 tons per hour, but the total cost for this combination is spread over the required output of 1103 tons per hour, resulting in a higher cost per ton.

The least cost combination of 8 trucks and 5 loaders has hourly capacity closest to 1103 tons per hour at 3.6 tons per hour under-capacity. Because the combination of 9 trucks and 4 loaders has the second smallest deviation in hourly capacity (+6.3 tons per hour) from the required 1103 tons per hour, it would be expected to display the second lowest cost per ton of output, but the combination of 8 trucks and 4 loaders actually represents the second best alternative. The cost difference is a function of the match ratio and the trade off between overtime and new investment. The better match ratio for the 8 truck-4 loader combination results in a more favorable interaction efficiency.

Within the decision making range, an additional machine unit has decreasing marginal productivity. If an eighth truck is added to the 7 truck-4 loader combination, total hourly production would increase by 90.0 tons, while a ninth truck would increase total hourly production by only 79.0 tons. Similarly, additional loaders, when added to a fixed number of trucks, have decreasing marginal productivity. For example, as a fifth loader is added to the 7 truck-4 loader combination, total hourly production increases by 48.10 tons, and a sixth loader would result in a production increase of only 28.5 tons per hour.

When relatively small increases in production are needed, the operator can obtain the production at less cost by working existing machines overtime and paying higher operating costs (overtime labor) rather than adding more units which increase total owning costs. Overtime operation decreases owning cost per ton by spreading a lower fixed cost over the same level of production. In fact, in each situation analyzed, the least-cost combination of loaders and trucks works some overtime to achieve the desired level of production; thus, it appears that a higher penalty is assessed against excess capacity than against under capacity.

Table 2 summarizes the costs per ton for selected machine combinations from Table 1. The group of low costs in the center of the matrix represents the decision making range. Very high costs appear in the upper right ($4.485/Ton) and lower left ($6.545/Ton) because loader and truck units are poorly matched. In the lower right, relatively high costs reflect excess capacity of both types of machines.

The result of changing to larger loading and hauling equipment is illustrated in Table 3. The optimal combination in this situation includes a smaller number of each type of machine (three loaders and six trucks); however, the cost of $0.729 per ton is essentially the same as the $0.730 cost for the smaller units.

With the smaller equipment (Table 2) the next lowest cost combination includes one less loader than the least cost combination; conversely, with larger equipment (Table 3) the next lowest cost combination includes one less truck. In both cases, investment and owning and operating costs are lower for the loader than the truck, which indicates that the next lowest cost combination does not always result from a change in one unit of the lower cost - lower investment machine.

Table 2. Summary Matrix of Cost Per Ton of Coal for 3-Cubic Yard Loader and 36-Cubic Yard Truck Combinations[a]

Number of Trucks	Number of Loaders						
	1	..	4	5	6	..	10
	------------Dollars per Ton ------------						
1	b		2.096	2.494	2.892		4.485
⋮							
5	1.486		0.812	0.859	0.906		1.175
⋮							
7	1.992		0.746	0.758	0.786		0.921
8	2.245		0.736	0.730	0.769		0.954
9	2.498		0.738	0.780	0.828		1.015
⋮							
15	4.016		1.088	1.138	1.188		1.381
⋮							
25	6.545		1.678	1.729	1.779		2.069

[a] Normal production hours in one shift - 1813
Needed average hourly production - 1103 tons
Optimal number of loaders - 5
Optimal number of trucks - 8
Cost per ton with least-cost combination - $0.730/ton
Investment per Loader - $106,865
Investment per truck - $146,593

Owning and operating cost per hour for 1 loader with no overtime - $39.38/hr
Owning and operating cost per hour for 1 truck with no overtime - $49.24/hr

[b] It is not physically possible for this combination to work enough hours to load two million tons of coal annually at the rate of 148.3 tons per hour. Therefore, this combination would not be physically feasible.

Changing to a double shift operation results in lower costs as illustrated in Table 4, and a shift from the optimal combination of 5 loaders and 8 trucks (Table 2) to 2 loaders and 4 trucks. Fewer machines are required; therefore, lower capital investment and fixed (owning) costs are spread over the same production. The result is a decrease of almost $0.10 in costs per ton. In the double shift operation (Table 4) the 4 trucks spend more time waiting to be filled than do the 8 trucks in the single shift operation (Table 1). In contrast, the 2 loaders in the double shift are more fully employed than the 5 in the single shift. With fewer machines required to obtain the annual output, costs increase faster as number of loaders or trucks is decreased from the optimal combination.

IV. SUMMARY AND CONCLUSIONS

High investment and operating cost require miners to make maximum utilization of the equipment they select. To fully utilize equipment, the individual units of the equipment set should be selected to attain the most profitable match ratio and

Table 3. Combination Owning and Operating Cost, Hourly Production and Cost per Unit of Production for 4 Cubic Yard Loaders and 51-Cubic Yard Trucks Loading Two Million Tons of Coal Annually in One Shift.[a]

Number of Trucks	Number of Loaders								
	2			3			4		
	Combination Owning & Operating Costs ($/hr)	Production (T/hr)	Cost per ton ($/T)	Combination Owning & Operating Costs ($/hr)	Production (T/hr)	Cost per ton ($/T)	Combination Owning & Operating Costs ($/hr)	Production (T/hr)	Cost per ton ($/T)
5	615.81	751.6	0.819	676.16	914.4	0.739	741.75	966.7	0.767
6	706.70	771.6	0.916	757.03	1038.2	0.729	817.34	1129.3	0.741
7	798.15	779.1	1.024	839.03	1128.1	0.760	904.77	1264.1	0.820

[a] Normal production hours in one shift - 1813 hours
Required hourly production to load and haul 2 million tons in 1 shift 1103 tons
Optimal number of loaders - 3
Optimal number of truckers - 6
Cost per ton with least-cost combination $0.729/ton
Investment per loader $152,655
Investment per truck $204,433
Owning and operating cost per hour for 1 loader with no overtime $50.30/hour
Owning and operating cost per hour for 1 truck with no overtime $66.13/hour

Table 4. Combination Owning and Operating Cost, Hourly Production and Cost per Unit of Production for 3-Cubic Yard Loaders and 36-Cubic Yard Trucks Loading Two Million Tons of Coal Annually in Two Shifts[a]

Number of Trucks	Number of Loaders								
	1			2			3		
	Combination Owning & Operating Costs ($/hr)	Production (T/hr)	Cost per ton ($/T)	Combination Owning & Operating Costs ($/hr)	Production (T/hr)	Cost per ton ($/hr)	Combination Owning & Operating Costs ($/hr)	Production (T/hr)	Cost per ton ($/T)
3	230.96	288.8	0.800	275.42	419.2	0.657	322.06	444.8	0.724
4	289.87	293.1	0.989	328.62	515.2	0.638	372.42	568.4	0.675
5	348.89	293.1	1.190	328.59	563.0	0.693	421.03	679.6	0.763

[a] Normal production hours in two shifts - 3625
Required hourly production to load and haul 2 million tons in 2 shifts - 552 tons
Optimal number of loaders - 2
Optimal number of trucks - 4
Cost per ton with least-cost combination - $0.638/ton

interaction efficiency. A mining cost generator and machine matching program were developed to calculate production and owning and operating costs for individual machines and then determine cost per unit of output for each combination.

The combination with the lowest cost per unit of output is optimal. The cost calculation reflects cost penalties for both under and excess capacity based on overtime operation and machine interaction efficiency. Hourly production, investment, and owning and operating cost per hour for each type of machine are the most important variables in determining cost per unit of output. The match ratio and interaction efficiency appear to become more important as the number of machines working in combination increases. The relative cost of under- and excess-capacity are determined by analyzing the impact on total cost and total production of a one machine increase or decrease of each type of unit in the combination, not by examining what that machine is theoretically capable of accomplishing by itself.

The results of the analysis for coal hauling indicate that the optimal number of loaders and trucks in combination changes with the mining plan. As the number of shifts increases, fewer machines are required. Therefore, lower total owning costs are spread over the same level of output, thus decreasing total cost per ton. In the cases examined, the least-cost combination always includes some overtime, which indicates that when small increases in production are required, overtime operation can attain the production at a lower cost per unit than through additional capital investment in equipment. If overtime were not available, the least-cost combination would include more equipment and have a higher cost per unit of output, which suggests that excess capacity is more costly than under capacity. Miners can use this program to calculate production, the costs of using specified sizes and numbers of machines, the effects of adding more machines and the level of overtime needed to meet specified levels of production.

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