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A Computer Simulation Model for a Surface Coal Mine

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Ein Computer-Simulationsmodell für einen Steinkohlen-Tagebau

Die Einsatzmöglichkeiten eines Simulators für ein Tagebau-Fördersystem zwecks Analyse von Abbau- und Terminplanung durch Erstellen und Auswerten von Alternativlösungen wird beschrieben. Im Tandem-Betrieb werden Abraum durch einen Schaufelradbagger und Kohle durch einen Löffelbagger gewonnen. Anhand des Modells ließen sich wertvolle Aussagen über mögliche Produktivitätssteigerungen durch den Einsatz weiterer Geräte und Verbesserung bereits im Einsatz befindlicher Maschinen machen.

Modèle de simulation sur ordinateur pour une mine de charbon à ciel ouvert

Application d'un simulateur de manutention de matériaux dans une mine à ciel ouvert pour l'analyse des problèmes de programmation et de planification à travers son développement et évaluation des autres possibilités. La surcharge est supprimée en utilisant ensemble un excavateur à roue à godets et une pelle excavatrice.

Modelo de simulación para una mina de carbón a cielo abierto

Se explica la aplicación de un simulador des sistemas de manutención para una mina de carbón a cielo abierto destinado a analizar los problemas de planificación y programación de la mina mediante la generación y la evaluación de diversas soluciones posibles. El descombrado se hizo con una excavadora de rueda de cangilones y una pala mecánica trabajando en tándem.

Summary

This paper describes the application of the open pit materials handling simulator (OPMHS) to a surface coal mine in Illinois. The mining method practiced is classified under the general heading *Area Mining*. The overburden is removed by a bucket wheel excavator (BWE) and a stripping shovel operating in tandem. The specific objective of the study was to demonstrate the application of the simulator to analyse mine planning and scheduling problems through the generation and evaluation of alternatives on the basis of simulated results.

On the basis of the simulation of the existing system, it is concluded that on the average, the system can perform to within 85% of the designed capacity. The performance of the stripping shovel was identified as the bottleneck in the system. However, the production can be increased to over 95% of the designed capacity by increasing the availability of the stripping shovel from 71% to 80%. Also, a number of plans to increase the prodution capacity of the mine by the introduction of new equipment was analysed.

1. Introduction

Coal production from surface mining has been on the increase ever since 1960; during the last 10 years coal production [1] from surface mining has grown enormously (Table 1). In fact, since 1974 the production from surface mining has exceeded that from underground mines. The US Federal Energy Administration [2] has predicted that surface mined coal would play an even more important role in meeting the projected production increase for the coal segment of the energy market (Table 2). Large production requirements from surface mines necessitate deployment of many large pieces of equipment. This equipment must be utilized efficiently by maintaining production at or near designed capacities. Basically, the problem is to select, size and schedule equipment to maximize production and minimize adverse environmental impacts [3].

The time, manpower, and cost limitations required to analyze a wide variety of situations and alternatives in planning designing, and scheduling equipment and methods for surface mines have been overcome with the application of simulation methods using a digital computer. Since the digital computer can be programmed to simulate the situations which are to be analyzed, many alternatives can be evaluated in a relatively short time. Input variables to the computer model (or simulator) are easily changed and the resulting changes in the system performance can be evaluated. When standard methods of analysis are applied, weeks and many man-hours are involved in analyzing a single design for the mining operations. Even then, many simplifying assumptions must be made since these operations are dynamic and transient. Hence, to make sound engineering decisions and to take proper and timely corrective actions, simulation methods are the only recourse.

This paper is concerned with the application of the Open Pit Materials Handling Simulator (OPMHS) developed by the Mining Engineering Section, The Pennsylvania State University.

2. The Open Pit Materials Handling Simulator (OPMHS)

A generalized flow diagram of the OPMHS model is shown in Fig. 1. The simulator consists of a number of interrelated sub-assemblies which represent various unit operations of a complex mining system. These include a BWE sub-assem-

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Table 1:
Bituminous and lignite coal production in the USA (National Coal Association, 1979)

Year	U.S. Total Coal Production (tonne)	Coal Production by		Percentage Distribution	
		Surface Mining Method (tonne)	Underground Method (tonne)	Surface	Underground
1968	494,638,000	182,521,390	318,811,550	36.9	63.1
1969	508,482,000	193,731,470	314,750,080	38.1	61.9
1970	546,971,000	239,573,150	307,397,520	43.8	56.2
1971	500,940,000	250,470,070	250,470,070	50.0	50.0
1972	540,125,000	263,213,960	276,003,910	48.9	51.1
1973	527,744,000	265,723,750	274,401,320	49.5	50.5
1974	547,401,000	297,785,970	249,614,710	54.4	45.6
1975	588,253,000	322,362,660	265,890,370	54.8	45.2
1976	603,278,000	337,835,580	265,442,240	56.0	44.0
1977	627,177,000	386,400,810	241,265,770	61.6	38.4
1978	603,393,000	383,693,770	219,699,270	63.6	36.4

Table 2:
New mine requirements (1975—1990)[1]
(after Federal Energy Administration, 1974)

	Business as Usual[3]	Accelerated Development[2]
Underground Mines:		
1 million tons	153	445
3 million tons	74	190
Surface Mines:		
1 million tons	110	195
3 million tons	25	90
5 million tons[2]	98	219
Total	460	1139

1 Including new mines to replace depleted productive capacity and new mines to increase existing productive capacity.

2 Although there are new 10-million ton surface mines in the West, and others are on the drawing board, for the purposes of this report nothing larger than a 5-million ton mine was considered. Checks with western surface mine operators indicate that the economy of scale is such that the cost of producing coal at a 10-million ton mine was considered the equivalent of two 5-million ton mines for the purpose of determining minimum selling prices, man-power requirements, equipment and supply requirements, etc.

3 Production targets for two cases.

1 short ton = 0.907 tonne

bly, shovel and dragline sub assembly, truck haulage sub-assembly and conveyor sub-assembly and the train sub-assembly. OPMHS simulates the total material handling of a mine operation and furnishes production and performance data for each system sub-assembly. For example, the basic aspects of the system that has been modeled may be brought into focus by referring to Fig. 2, a schematic diagram of a typical surface mining operation. A multi-stage materials handling scheme is employed to mine and move materials from multiple origins (Pits 1 and 2) to several destinations (bins, waste disposal sites, etc). The system is a complex, dynamic network with several interconnected networks. Consequently, in OPMHS all decision points are defined and coordinated such that the system status (data, information, frequency of operations, etc.) is updated for each time interval Δt. The length of the interval, Δt, and the total simulation time, T, are defined by the user at the beginning of simulation. The system is interrogated and updated from 0 to T in interval of Δt. For example, during any time period (t) to ($t + \Delta t$) the system status at (t) is updated by the information generated during the interval Δt to provide the system status at ($t + \Delta t$). Thus, the information generated at a time interval Δt affects all subsequent decisions. Each of the sub-assemblies may or may not be active in any particular simulation since not every surface mine would have all of these methods for materials handling. Only those sub-assemblies which are required can be used. Besides, the sub-assemblies are used in the particular sequence the user defines. One major advantage is that once the basic mining plan and sequences have been selected, rapid evaluation of various projected mining configurations can be made. This information can then be used for equipment selection, operational procedures, and monitoring and control of the selected mining practice. Thus responsive management information is provided as well as sound engineering decisions made as illustrated in the following application [5].

2.1 Application to an Illinois Mine

As is typical throughout the central coal basin of the USA, the topography of the area where the selected mine is located is generally flat. The strata overlying coal seam (Illinois No. 6) consists of clay, sand and gravel, medium hard shales, sandstone and some limestone. A stratigraphic column of the overburden and coal seam at the selected mine is shown in Fig. 3. The mining method praticed at this location can be classified as *area mining.* The operation consists of a single pit extending east to west with highwall to the north. The pit which is approximately 1920.24 m long, varies in width from 39.62 m to 45.72 m, with coal loading restricted to a width of 18.29 to 24.38 m. The mine has a current annual production of 1.09 million tonne of coal. The major stripping equipment includes a German BWE and a 61.16 m^3 stripping shovel. The BWE and the stripping shovel operate from the top of coal. Fig. 4 shows a section view of the cut. Exposed coal is loaded into 90.71 tonne bottom dump coal hauler by a 5.35 m^3 loading shovel. For overburden removal the BWE and the stripping shovel are scheduled for 24 hours a day, seven days a week and 364 days a year. The coal loading shovel, however, is scheduled for two shifts a day, five days a week, and 240 days a year. At the mine, the BWE and the stripping shovel take varying heights of overburden. The height of the BWE bench can vary from 4.87 m to 6.09 m. The shovel bench can vary from 12.19 m to 21.33 m. In effect, the required ratio between the shovel and BWE production can vary from 2.0:1 to 4.4:1. In 1976, for example, the overall stripping ratio

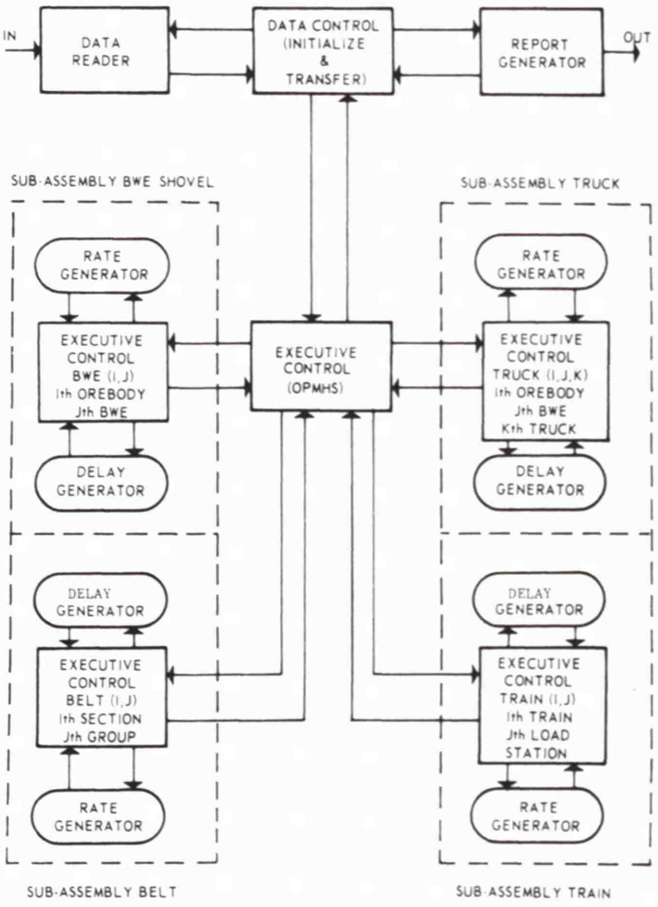


Fig. 1: Generalized flow model of OPMHS

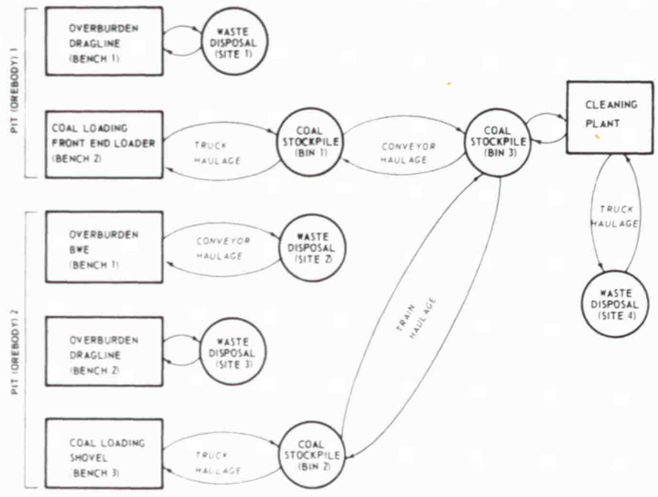


Fig. 2: Conceptual operating system

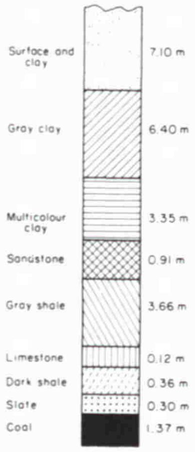
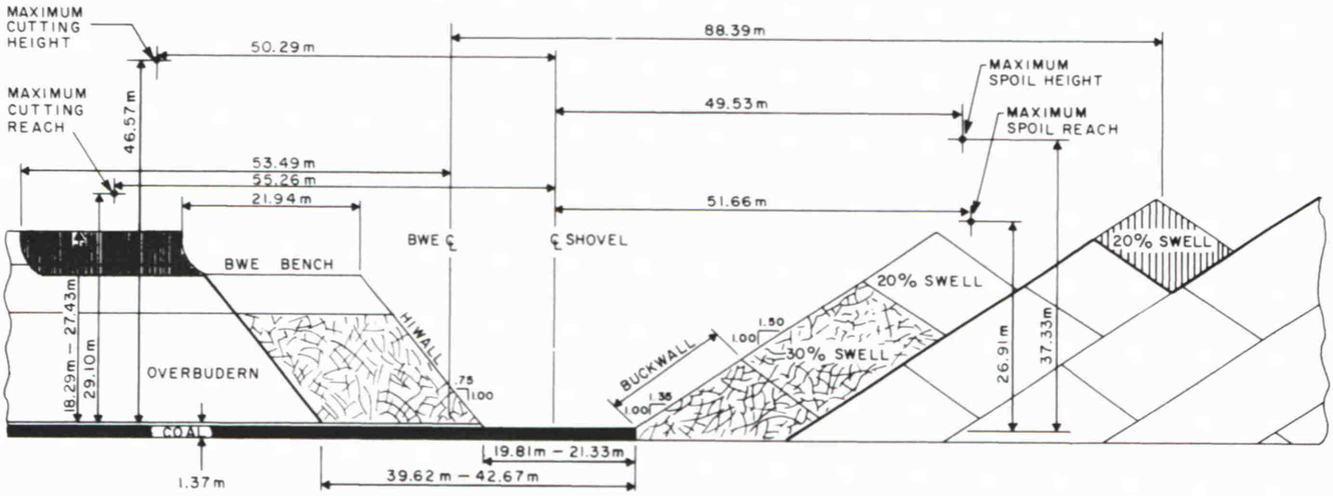


Fig. 3: Stratigraphic column



MAXIMUM CUTTING HEIGHT AND REACH, AND MAXIMUM SPOIL HEIGHT AND REACH ARE FOR THE STRIPPING SHOVEL.

Fig. 4: A section view of the cut

(m³/tonne) was 17.22, and the match ratio was 4.4:1. The stripping shovel, however, can take overburden up to 21.33 m and helps out the BWE where the total overburden is less. In view of the great variability in the match ratio and in the operations, the analysis chosen for the mine is based on the following average conditions:

— Average overburden thickness	21.33 m
— Average coal thickness	1.37 m
— Height of BWE bench	6.09 m
— Match ratio	2.5:1
— Annual coal production	1.09 million tonne

The stripping ratio, computed directly from drill hole maps for an overburden thickness of 21.33 m is 12.14 m³/tonne. Since the coal has a reject of 20%, the stripping ratio for clean coal, assuming 100% recovery is 15.17. The average stripping ratios for raw and clean coal at the time of the mine visit were 12.47 and 15.59 respectively.

On the basis of the above planned annual clean coal production, the average raw coal production per shift is:

$$\frac{(1{,}090{,}000)}{(0.8)\ (240)\ (2)} = 2{,}835 \text{ tonne/shift}$$

On the basis of 21 shifts of overburden removal per week, 10 shifts of coal removal per week and an average stripping ratio of 12.14 for the required raw coal production of 2835 tonne/shift the overburden volume to be removed each shift is:

$$(2835)\ (12.14)\ \frac{(10)}{(21)} = 16{,}389\ \text{m}^3$$

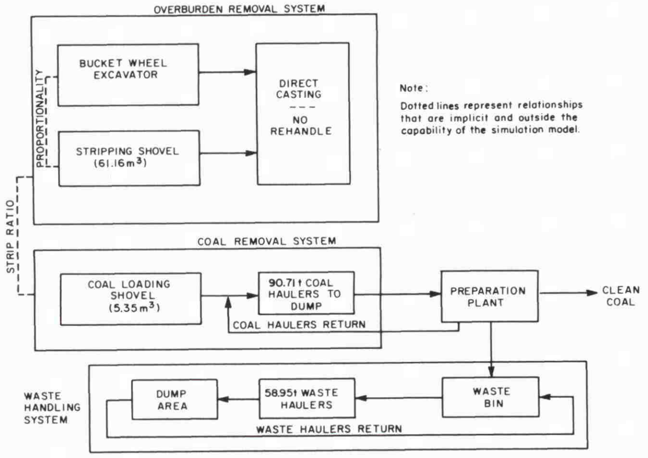
On the basis of the match ratio of 2.5:1, the stripping shovel should remove each shift 11,706 m³ and the BWE, 4,683 m³.

The mine haul roads are generally flat and appeared to be in good condition. Two areas having significant grade are at the pit incline (6%) and at the ramp to the dump (5%). The average one way haul distance is 6,678.78 m. Coal preparation plant refuse is trucked to previous cuts or haulage inclines in the mined area by 58.96 tonne end dump trucks. The one-way haul distance is approximately 2,414.01 m. Fig. 5 is a flow diagram of the material handling system.

3. Computer Simulation

The following sub-assemblies of the OPMHS were used in this application:

1. BWE sub-assembly
2. Shovel sub-assembly
   a) Overburden removal
   b) Coal removal
3. Truck sub-assembly
   a) Coal transport
   b) Waste transport



Note:
Dotted lines represent relationships that are implicit and outside the capability of the simulation model.

Fig. 5: Flow diagram of the materials handling system

Data for the application was obtained through time studies, discussions with mine personnel, from mining engineering records, and from equipment manufacturers' catalogs. The input requirements for operation of the BWE sub-assembly are shown in Tables 3 and 4. Table 5 shows the input requirements for the shovel sub-assembly. The input requirements for the truck sub-assembly (for coal and waste transport) are given in Table 6. Additional input information required for the truck sub-assembly is the profile of haulroads and truck speed-rimpull information which were obtained from the mine maps and manufacturer's catalog, respectively.

An initial simulation of the existing system (base case) was made to validate the simulation model. In each computer run the operation was simulated for ten shifts but for the purpose of the analysis, the results were averaged per shift. Table 7 shows a production summary of the output from this run. The total overburden removed is 14,332 m³/shift which is less than the required production of 16,389 m³ by 2,057 m³. Of this amount, the tripping shovel removes 9,873 m³, and the BWE removes 4,459 m³. The simulated results indicate that in the overburden removal system, the stripping shovel and BWE productions are fairly matched. However, the match ratio 2.21 indicates that in the longrun, the BWE will wait on the shovel.

The required overburden removal for a coal production of 2,868 tonne/shift at a strip ratio of 12.14 is 16,580 m³. However, the actual amount of overburden removed is only 14,332 m³. The effect of this imbalance between the overburden and coal removal systems can be seen in the decreased strip ratios. In the long run, the coal loading

Table 3: Soil characteristics of top 6.09 m of overburden

Soil Type	Specific Cutting Resistance kg/cm	Boulder Occurrence Frequency	Wheel Speed Fraction of Maximum Speed	Bucket Fill Factor Fraction of Theoretical Capacity	Swell Factor (Bank Volume/ Loose Volume)
Topsoil and Clay	Range 28—42 Mean 35	0	0.40	0.95	0.80

Table 4:
Input data for BWE subassembly

Description	
Number of soil types in the system	1
Soil Type	1
Bucket filling capacity of the soil	0.95
Cutting resistance of the soil, kg/cm	35
Ratio of allowable cutting speed to maximum cutting speed	0.40
Swell factor of the soil	0.80
Number of observation towers for trucks	0
Number of BWEs, shovels or draglines in the orebody	3
Wheel diameter of the BWE(m)	9.2
Crawler speed of BWE(m/s)	0.073
Length of the wheel boom for BWE(m)	48.31
Capacity of the bucket of BWE (m^3)	0.99
Number of buckets on wheel of BWE	8
Maximum advance of BWE before next cut(m)	18.28
Weight of the superstructure of BWE(kg)	249,480
Total weight of the BWE(kg)	2,169,115
Crowding BWE (Non-crowding BWE = 0)	1
Frictional resistance at the ball race for BWE(%)	3
Radius of the ball race for BWE(m)	6.0
Average stop time for boulder hit for BWE(s)	0
Mean maneuvering time for BWE(s)	600
Maximum slewing angle to left of line of advance (radians)	0.52
Maximum slewing angle to right of line of advance (radians)	0.32
Slope of bench for BWE	0
Mechanical availability	0.46
Continuous run time for BWE(s)	600
Initial material being cut (1 = ore, 2 = waste)	2
Surge bin capacity of BWE(tonne)	272,155 ore 272,155 waste
Number of benches to be cut by BWE	1
Height of bench in orebody for BWE(m)	6.09 for left side 6.09 for right side
Probability of not hitting a boulder in ore body	1
Material density (kg/m^3)	2.40
Ore to waste ratio	0
Floor rolling resistance(%)	2
Floor slope encountered by BWE(%)	0
Tail bin number	1

Table 5:
Input data for shovel subassembly (for stripping and coal)

	Stripping Shovel	Coal Shovel
Diameter of the wheel(m)	0.0	0.0
Mean cycle time(s)	60.0	30.0
Deviation from cycle time(s)	10.0	2.0
Maximum cycle time(s)	72.0	32.0
Minimum cycle time(s)	53.0	28.0
Bucket capacity(tonne)	93.44	4.71
Deviation of bucket capacity(tonne)	4.53	0.0
Maximum bucket capacity(tonne)	97.97	4.71
Minimum bucket capacity(tonne)	88.90	4.71
Ore to waste ratio	0	1
Mechanical availability	0.71	0.95
Continuous run time(s)	3000.0	3000
Capacity of surge bin (ore),(tonne)	272,155	0.0
Capacity of surge bin (waste),(tonne)	272,155	0.0
Tail bin number for face excavators:	2	3

1 short ton = 0,907 tonne

Table 6:
Truck data

Truck Type	Type 1[1]	Type 2[2]
Mean payload(tonne)	58.96	90.71
Empty weight tonne)	36.87	54.43
Mean dump time(s)	10.0	10.0
Mean maneuvering time(s)	15.0	10.0
Maximum acceleration rate(m/s^2)	0.15	0.15
Mechanical availability	0.9	0.9
Continuous run time(s)	3000	3000

[1] WABCO 65A
[2] Athey Model PH660

system will wait on the overburden removal system. Since the coal shovel works for over 93 % of the time, the system is also reaching a limiting capacity with regards to coal loading.

At the time of the mine visit, coal was loaded only three days a week, two shifts/day. Unless the demand for coal increases to the extent that the mine starts loading coal 10 shifts a week and at a rate 2,835 tonne/shift, the imbalance between the BWE and shovel productions, and the overburden and coal removal systems should not pose major problems. However, on the basis of the above analysis, assuming that demand for coal will increase to the planned capacity, the recommended short term plan called for the increase in the production from the shovel so that the shovel and BWE productions are better matched, and the BWE does not wait on shovel.

In simulation run 2 all input data used in the base case were held constant except the stripping shovel's availability which was increased to 80 %. The results are abstracted in Table 8.

The only way to increase the availability of a machine is to make a detailed analysis of the machine application to identify areas for potential improvements. This entails collection of records for the machine activities over extended periods of time. The operating times and the delay times should be broken down into specific independent categories and data collected on each category. These categorized records can then be evaluated for possible improvements. Even small changes in the mode of operation can increase the availability and performance of the machine. For example, deadheading is usually a major source of operational delays. The deadheading operation is greatly dependent on the pit layout and mine dimensions. Advance planning and preparation can reduce the total overall maintenance delays and therefore increase the machine availability.

From Table 8, it can be seen that in the overburden removal system, the performances of shovel and BWE are fairly matched. If the coal shovel loads 2,836 tonne, it will catch up with the overburden removal system since more coal is loaded than is being uncovered as indicated by the 12.14 stripping ratio. Therefore, the overburden removal capacity for the system must be increased. Since the stripping shovel is operating at its maximum availability, an increase in the shovel production is not possible. In the longrun, increases in BWE production will not increase total overburden

Table 7: Production summary for simulation run 1

	Availability			Average Overburden Depth (m)	Average Raw Coal Production (tonne)	Strip Ratio[2] (m^3/tonne)		Overburden Removal			Match Ratio[1]
	BWE	Stripping Shovel	Coal Shovel			Raw Coal	Clean Coal	BWE (m^3)	Stripping Shovel (m^3)	Total (m^3)	
Actual data averaged for a shift	0.46	0.71	0.95	21.33	2835	12.14	15.17	4679	11705	16384	2.5
Simulation run 1 (base case)	0.46	0.71	0.95	21.33	2868	10.50	13.12	4460	9873	14333	2.21

1. Match Ratio = $\frac{\text{Shovel production, m}^3}{\text{BWE production, m}^3}$

2. Raw Coal Strip Ratio = $\frac{\text{Total overburden removed, m}^3}{\text{Average raw coal production, tonne}}$

Raw coal strip ratio = clean coal strip ratio x 0.8

Calculations are based on 10 shifts of coal production and 21 shifts of overburden removal per week.

Table 8: Production summary for simulation run 2

	Availability			Average Overburden Depth (m)	Average Raw Coal Production (tonne)	Strip Ratio[2] (m^3/tonne)		Overburden Removal			Match Ratio[1]
	BWE	Stripping Shovel	Coal Shovel			Raw Coal	Clean Coal	BWE (m^3)	Stripping Shovel (m^3)	Total (m^3)	
Actual data averaged for a shift	0.46	0.71	0.95	21.33	2835	12.14	15.17	4679	11705	16384	2.5
Simulation run 1 (base case)	0.46	0.8	0.95	21.33	2836	11.87	14.38	4430	11598	16028	2.61

1. Match Ratio = $\frac{\text{Shovel production, m}^3}{\text{BWE production, m}^3}$

2. Raw Coal Strip Ratio = $\frac{\text{Total overburden removed, m}^3}{\text{Average raw coal production, tonne}}$

Raw coal strip ratio = clean coal strip ratio x 0.8

Calculations are based on 10 shifts of coal production and 21 shifts of overburden removal per week.

Table 9: Production summary: long term plan

	Availability			Average Overburden Depth (m)	Average Raw Coal Production (tonne)	Strip Ratio (m^3/tonne)		Overburden Removal			Match Ratio
	BWE	Stripping Shovel	Coal Shovel			Raw Coal	Clean Coal	BWE (m^3)	Stripping Shovel (m^3)	Total (m^3)	
Simulation run 3 Plan 1	0.50	0.70	0.95	21.33	3551	10.71	13.38	4811	13309	18120	2.76
Simulation run 4 Plan 2	0.55	0.75	0.95	21.33	3576	11.56	14.44	5282	14397	19679	2.72
Simulation run 5 Plan 3	0.65	0.80	0.95	21.33	3507	12.88	16.10	6240	15269	21509	2.44
Simulation run 6 Plan 4	0.65	0.80	0.95	21.33	4010	11.33	14.16	6240	15398	21638	2.46

1 short tonne = 0.907 tonne

removed per shift since the performance match in the overburden removal system will be unfavorable to the shovel and the BWE has to wait on the shovel.

These simulation runs confirm that the maximum productive capacity of the present system is approximately 2,722 tonne/shift, assuming availabilities of 95% for the coal shovel, 46% for the BWE and 80% for the stripping shovel. The total overburden removal capacity under these assumptions is 16,028 m³. Since the designed capacity of the mine is only 1.09 million tonne/year of clean coal (2,835 tonne/shift of raw coal), the present system can perform to within 97% of its designed capacity, if the stripping shovel availability is increased to 80% from the current 71%.

4. Longterm Plan

Any plan for production improvement over 2,722 tonne/shift will require new equipment for overburden removal. In an earlier study at this mine, performed by a management consultant [6] under contract to US Bureau of Mines, it was recommended to replace the existing 61.16 m³ shovel with a 85.63 m³ shovel, and the existing 5.35 m³ coal shovel by a 7.64 m³ shovel. No changes were proposed with regard to the BWE, the coal haulers and the waste haulers. These recommendations were evaluated on the simultator. Several plans (Plan 1, Plan 2, Plan 3, and Plan 4) were designed and the system performance was studied. The results of the simulations are summarized in Table 9. Plan 1 and Plan 2 are not satisfactory for following reasons:

1. From the strip ratios, it can be seen that more coal is being loaded than is being exposed. There is not adequate overburden removal capacity in the system to sustain this production.
2. More importantly, from the match ratios, it can be seen that the overburden removed by shovel is higher than that removed by the BWE. The performance match in the overburden system is unfavorable to shovel. In the longrun the shovel will wait on the BWE.

The following conclusions can be made based on the alternatives designed for longterm improvement:

1. The maximum production capacity that can be achieved is approximately 3,511 tonne/shift, assuming a 95% availability for the coal loader, 65% availability for the BWE and 80% for the stripping shovel.
2. Although the coal loading shovel is waiting on coal hauler any increase in the number of coal haulers will not increase production. In practice, the coal loading system will wait on the overburden removal system.

5. Final Comment

The complexity of surface mining operations is increasing as attention is directed towards mining deeper coal seams with larger equipment than heretofore. Whereas selection of equipment and initial pit design can be done through standard engineering procedures, the interactions in a complex system due to changes in operating procedure and equipment can be accurately evaluated only through the application of simulators such as OPMHS.

Acknowledgements

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