PROBLEM 6

STRATEGIC PLANNING AND OPTIMIZATION IN AN OPEN-CUT COAL MINE

1. INTRODUCTION

Capricorn Coal Pty. Ltd. (Capcoal) is the operating company for the German Creek mine near Middlemount in the Bowen basin of central Queensland. The mine has been producing since mid 1982, initially by open-cut strip mining and since 1984 augmented by an underground colliery. Known reserves are 100 million tonnes of open-cut coal and about 1000 million tonnes of underground coal.

A mine must operate in an everchanging economic environment of fluctuating coal prices, increasing development costs, and growing knowledge of reserve quality and mine geology. Companies need confidence that risk has been properly understood and assessed before committing capital for additional development. Also, tools which can be used to acquire an appreciation of how current actions will constrain future development opportunities, or restrict planning flexibility in later years, will be of help in timing current mining plans and in deciding the worth and timing of proposed developments.

The problem proposed for solution involves modelling the interaction between all mining stages over the life of the open-cut mine. At present there are 9 open-cut pits and 3 underground mines. The coal seams, the major one being the German Creek seam which is of the order of 2 metres thick, dip into the ground in an easterly direction. The various pits are strung from south to north with the better grade coal being in the southern part of the base (see Figure 1).

The mining process for each pit is carried out in strips which stretch lengthways across the pit and are approximately 80 metres wide and one to two kilometres long (see Figure 2).

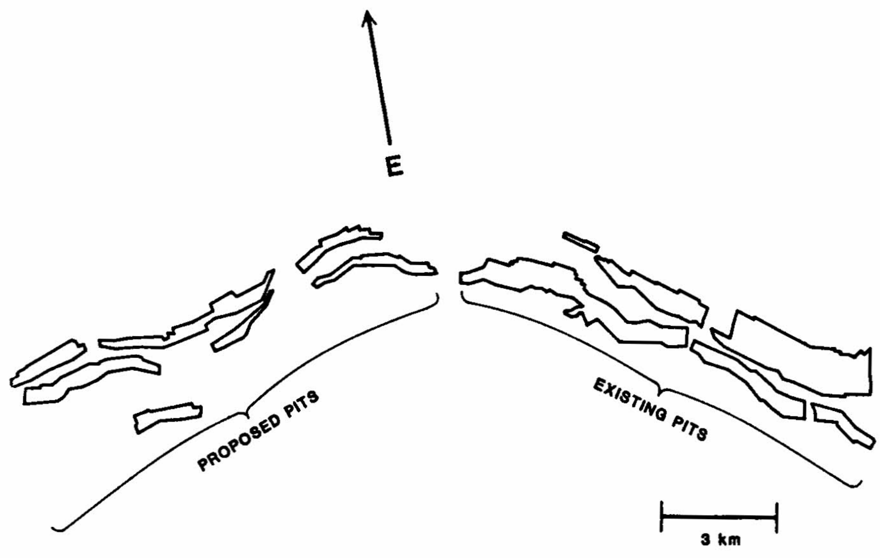

Figure 1. Illustrating the layout of the pits.

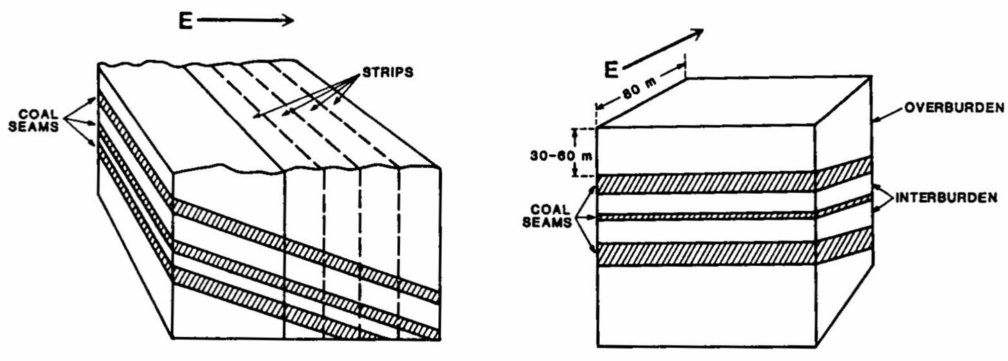

Figure 2. Illustrating the strips and the coal seams.

The various stages for mining a strip are as follows. Firstly the thick layer of overburden is removed from the strip by a dragline. This waste is deposited into the previously mined strip. Once the coal seam has been exposed, the coal can be mined and hauled to the washing plant for treatment. If there are several coal seams in a strip, which is usually the case, the material lying above the next coal seam, interburden or parting, must be removed before the next coal seam is mined. The interburden layer may be several metres thick and the coal seam is exposed by having specialized equipment shift the interburden within the strip. This process is repeated until the strip is mined to its economic limit.

There are several constraints on the system, the main ones concerning the draglines and their operations. Draglines are very expensive pieces of equipment and at present there are only four which must cover the nine pits. The company feels that it is not economical to purchase any more so this is a tight upper bound on the operation of the mine, particularly when it takes a dragline three to nine months to clear a strip. Once a dragline has finished a strip it is then walked to its next scheduled pit. Although walking time is brief relative to stripping time, it is still a period when the dragline is unproductive. The overburden removed by the dragline is dumped into the previous strip so all coal must have been mined from that strip. For safety reasons, no mining can be carried out within 100 metres of the draglines. Although the mining, hauling and interburden removal fleets are also constrained in size, to some extent the fleets are large enough and fast enough to be more easily manipulated than the dragline.

Once the coal has been removed from a strip it is taken to an intermediate stockpile before treatment at the washing plant to produce the final product. This product is a high quality coking coal used in steel manufacture and must satisfy several specifications, the main one being ash content which must be no greater than 8.5%. This product can be made in a number of ways, depending on the blend of good quality and poor quality coals used in the washing process.

The questions the company needs addressed are:

i. What is the optimum economic lifetime of the mine?

ii. What types of products will maximize the nett present value of the mine?

iii. What is the optimal timing of new open-cut and underground developments?

iv. What dragline schedules are optimal?

v. How sensitive are the various decisions to inaccuracies in reserve and quality estimates?

All of these items, of course, interact. The economic lifetime of the mine depends on the number, types and timing of products. For instance, if only one product is made requiring a high quality coal input, then once the high quality coal has been mined out the open-cut mining will cease; whereas if several were made of different quality, then by blending good coal with poor coal, the economic lifetime and the return on the investment in the mine may increase. At each period of time the types of products the company can make will depend on the different grades of coal being mined, which in turn depend on the location of the draglines. A model of the system is displayed in Figure 3.

2. IMPORTANCE OF THE DRAGLINES

To try to tackle the whole problem at once is obviously a difficult task and so we decided to ignore the question of underground mines and to start with the most limiting of the various factors, the draglines. For this preliminary analysis we assumed that the lifetime of the mine, say 10 years (this could be varied so it would not necessarily assume knowledge of the answer to the first question) was broken up into 3 month periods and, in each of these periods, the four draglines must be assigned amongst the nine pits. (If a pit requires say 6 months to strip then we could divide it into 2 pits or more generally change the periods to one month, but for the sake of argument we can leave it as is). We assume that each dragline stays in that pit until the next period when it is assigned a new pit. You will notice that no mention has been made of which strip in a pit the dragline works but, as there is only one strip available at any time due to the constraints on the operation of the dragline, this is not necessary.

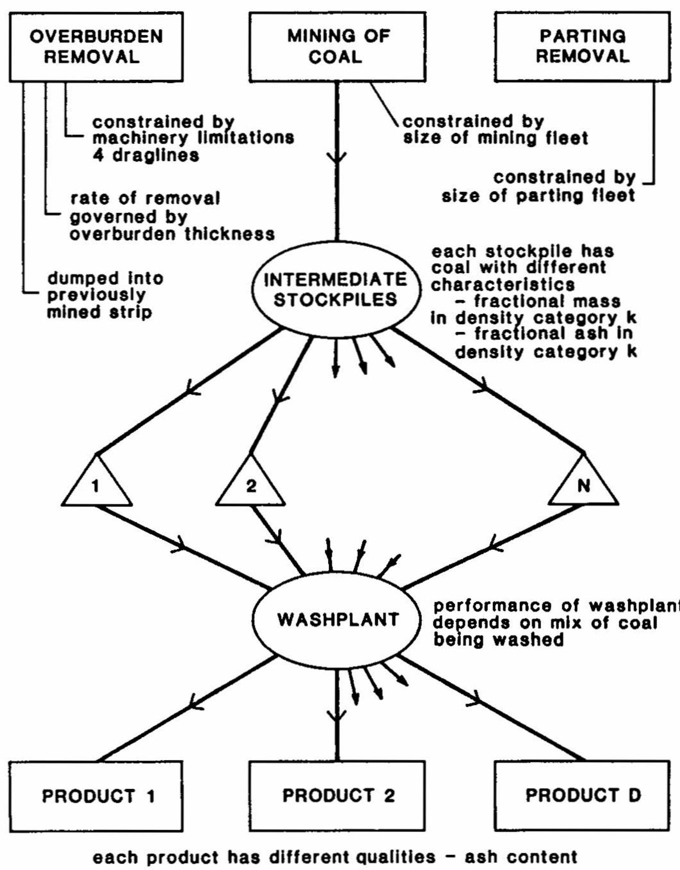

Figure 3. Factors to be considered in scheduling the mine's operations.

To determine the optimal dragline schedule, we start with a feasible assignment of the draglines in each period, over the planning horizon. So, in the first period, the four draglines are assigned to four of the nine available pits. However, in the second and later periods, there is less flexibility in the assignments since no dragline can work a pit that currently is being mined. This means that none of the pits worked the previous period by the draglines can be assigned since mining operations would still be in progress. So, besides the first period, there are only five possibilities to choose from when assigning the four draglines.

Once the dragline schedule has been chosen we need to assign a value to it corresponding to its worth. Amongst the factors that contribute to the value are the distances travelled by the draglines, the cost of mining and parting removal, the costs of washing of the various grades of coal and the return from the sale of the products. We must also take account of the discount factor in determining this value. The returns in later periods are discounted more heavily than returns in say the first year of operations. This value then should hopefully give the operators some idea on how to improve the scheduling of the draglines.

So the general outline of a dragline scheduling algorithm can be given as

Algorithm

1. Given the current dragline schedule, calculate the cost of mining in each period.

2. Use a subroutine to determine the best mix of products to utilize this coal and maximize profit.

3. Including a discount factor, sum the profits for this schedule over all

time periods, thus giving the value of this schedule. If satisfactory, stop, otherwise continue to find better schedule.

4. Using the information obtained in steps 1 and 2, perturb the current schedule to one of higher value. Go to step 1.

The final step, step 4, could be performed in a number of ways, for instance, by using some type of travelling salesman method or say simulated annealing. However the most practical way would probably be to let the controlling engineer use his experience and the information obtained in the previous steps to adjust the dragline schedule. As far as step 1 is concerned, Capcoal's existing dragline simulation programs can be used. These programs calculate, for each dragline, where it will be in each pit and thus the quantity and quality of coal it uncovers in the period.

3. COAL BLENDING

The most difficult part of the algorithm is finding a subroutine that will satisfy the requirements of step 2. The remainder of this discussion will be concerned with establishing the general framework of this subroutine and, in so doing, satisfying many of the objectives outlined earlier.

Let us look at one 3 month period. Part of the value attributed to the scheduling of the 4 draglines in their present four pits is given by the cost of overburden removal, mining and parting removal. There is enough data available to make that calculation straightforward. The other part of the value in that period is determined by the product mix and the washing process, which we shall now model. As in Figure 3, assume there are N intermediate stockpiles and D products.

For each $d = 1,2,..,D$, let

x_n^d = proportion of raw coal used to make product d taken from stockpile n (the d is a superscript, not an exponent),

T^d = tonnes of raw coal used to make product d,

T = number of tonnes of raw coal the washing plant can process in one period.

and, for each n = 1,2,..N, let

Q_n = tonnes of raw coal in stockpile n.

These definitions lead to some constraints on the system:

$\sum_{n=1}^{N} x_n^d = 1$ for all d, fractions in product d must sum to one,

$\sum_{d=1}^{D} T^d \leq T$ wash plant capacity cannot be exceeded,

$\sum_{d=1}^{D} x_n^d T^d \leq Q_n$ for all n, tonnes of coal taken from stockpile n cannot exceed Q_n.

Each product d will have different specifications and so will require different blends of coal $x^d = (x_1^d,\ldots,x_N^d)$. The recovery rate in the washing process depends on several factors, one of which is the blend x^d; if there is more good coal the recovery rate is higher and moreover the recovery rate of blended coal can be higher than when the component coals are washed separately. The recovery also depends on the density ρ^d of the flotation medium used. To avoid circuit overload, ρ^d must be constrained, and the lower limit will depend on x^d. Looking at each period in isolation, the optimization problem that must be solved to obtain the value of an assignment in one period is as follows:

$$(\Omega) \quad \underset{\underset{\sim}{x},\underset{\sim}{\rho},\underset{\sim}{T}}{\text{maximize}} \sum_{d=1}^{D} p^d P^d$$

subject to

$$P^d = T^d \sum_{n=1}^{N} x_n^d F_n(\rho^d) \qquad \text{for all } d,$$

$$\sum_{n=1}^{N} x_n^d H_n(\rho^d) \leq 0 \qquad \text{for all } d,$$

$$\sum_{d=1}^{D} x_n^d T^d \leq Q_n \qquad \text{for all } n,$$

$$\sum_{d=1}^{D} T^d \leq T,$$

$$\sum_{n=1}^{N} x_n^d = 1 \qquad \text{for all } d,$$

$$\rho_{min}(x^d) \leq \rho^d \leq \rho_{max} \qquad \text{for all } d,$$

where

$$\underset{\sim}{x} = (x^1, x^2, \ldots, x^D),$$

$$\underset{\sim}{\rho} = (\rho^1, \rho^2, \ldots, \rho^D),$$

$$\underset{\sim}{T} = (T^1, T^2, \ldots, T^D),$$

p^d = profit per tonne of product d,

P^d = tonnes of product d,

F_n = function relating flotation density to recovery,

H_n = function relating flotation density to product specifications.

The second constraint signifies that each product must satisfy certain specifications - in particular, ash content. This is a nonlinear programming problem and can be solved by a number of methods. If there are only two products and two stockpiles, then $\underset{\sim}{x}$ has four components, $\underset{\sim}{\rho}$ two and $\underset{\sim}{T}$ two, so that it is small enough to be solved without too much difficulty. Subject to a question of convergence, a particularly simple method is the following:

1. Fix $\underset{\sim}{x}$ and $\underset{\sim}{\rho}$ in (Ω) and maximize to find the best value of $\underset{\sim}{T}$.

2. With the same $\underset{\sim}{\rho}$ as in step 1 and $\underset{\sim}{T}$ as determined in step 1, maximize to find the best $\underset{\sim}{x}$.

3. With the same $\underset{\sim}{T}$ as determined in step 1 and $\underset{\sim}{x}$ as determined in step 2, maximize to find the best $\underset{\sim}{\rho}$.

4. Use the latest value of $\underset{\sim}{x}$ and $\underset{\sim}{\rho}$ and return to step 1.

This has the advantage of decomposing (Ω) into simple subproblems: for instance, step 1 amounts to solving a small linear programming problem. Of course there are more sophisticated techniques for solving a problem such as (Ω), but the aforementioned method has the advantage that Capcoal already has the software to solve the simple type of subproblems contained in steps 1 to 3. After running through steps one to four enough times to obtain an acceptable solution, one then has the value of the dragline assignment in that period as well as the best mix of products. However, this ignores the possibility of holding over some coal to later periods whereby one could improve the value further. To handle this one could, say, lump three periods together and solve (Ω) over these three periods. The problem would still be small enough to be readily solvable, and the subproblems in steps 1 to 3 would be of the same simple type as before. Once this has been done, the first period could be omitted from the three and another added; in effect, we would have a moving window of three periods.

So this last algorithm will give a value to each schedule, and, if it includes this last modification where more than one period is taken into account at a time, the value will be made up of both short term and long term benefits. The nett present value of the mine is then simply the value of the best schedule and the best product mix is obtained from the values of $\underset{\sim}{T}$ over the total number of periods. (If for some d the component T^d is small, or even zero in most periods, then this possible product should be eliminated). If this problem is run over several planning horizons so that the initial choice of time scale is not restrictive, then the period after which all values are negative, so that marginal cost outweighs marginal profit, will determine the economic lifetime of the mine. Sensitivity of all these decisions to changes can be obtained from the shadow prices arising from the optimization algorithm that finds the value in each period. These shadow prices, along with other factors such as which stockpile is depleted in each period, also give useful information to determine how to perturb a non-optimal dragline schedule into a better one.

One of the most important features of this method is that it essentially decomposes into several small problems which are easy to understand and their analysis provides a tool to assist management in updating or changing a dragline schedule or product mix. It also enables management to pick out the more binding constraints which restrict performance and the areas which need special attention so that the true worth of the schedule can be obtained.

4. CONCLUSIONS

Certainly, the above does not give a detailed description of the method of solution. Of course, this was never feasible given the amount of time the group had to study the problem. However, it does provide the basic structure and directions from which the necessary details can be deduced. In general, it was an enjoyable experience for the members of the group who were able to share their expertise and each provide their own valuable input. However, most credit for the success of this project must go to the Capricorn Coal representative, Tony Henzell, who not only could answer our questions about the physical workings of the mine, but also had done considerable work in setting up mathematically several aspects of the problem. Liaising between people of different training is often difficult and to have someone with a mathematical background who was familiar with the problem made the process much simpler.