Planning of Underground Copper Mining

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SYNOPSIS

As part of the planning system at each division of Nchanga Consolidated Copper Mines, Limited, the Mine Planning Department is required to produce a detailed production schedule for each shaft.

Because of the difficulties in producing a schedule which satisfies all the mining constraints, and because of the large clerical effort involved, the full range of possible schedules can never be considered.

It has been found possible to produce a schedule using linear programming which satisfies the majority of the many varied mining constraints. Computer programs have been written to enable the mine planning department to use this mathematical system without assistance.

The system has a large degree of flexibility to enable the planner to include conditions which cannot be incorporated readily in the linear program. This system permits the more efficient production and evaluation of schedules and reduces the amount of clerical effort.

INTRODUCTION

Each year overall company targets are set for copper production by Nchanga Consolidated Copper Mines, Limited. The overall company target crystallizes into more specific targets for individual divisions of the company and thence to targets for individual ore sources. When the annual target has been set for an ore source, a plan is produced which details the ore to be mined each month and the monthly tonnages of copper to be produced.

Initial production schedules are produced up to six months in advance of the year under consideration in order to co-ordinate the plans for the whole company and to produce a metallurgical plan for ore treatment. After final approval by company management, the planned copper output is largely sold in advance under contract. Consequently, once a plan has been accepted, there is great financial pressure to produce the tonnages quoted.

It is usually possible to produce from each ore source the planned monthly copper tonnage, but due to unforeseen circumstances, the actual ore mined often differs from that planned. The annual plan is revised at six-monthly intervals to take account of these variations, but in a manner that it still complies with the originally set copper target.

The Mine Planning Department of the Rokana Division of the company is responsible, as part of its duties, for producing schedules for three underground ore sources operated by the Division.

The planner will attempt to produce a schedule, based on his mining experience, which satisfies the overall copper requirement and also all the other mining considerations. This schedule is invariably amended several times following discussion with the appropriate underground manager and may then require further revision because of changes in the company plan.

Concern was expressed by the Rokana Mine Planning Department at the amount of work involved in producing and amending schedules, and the Operational Research Department was asked if it could assist in the solution of this problem.

DESCRIPTION OF MINING

The Rokana orebody is a stratiform deposit and the average thickness, dip and ground conditions make it suitable for sub-level open stoping.

In general, the orebody is divided over its entire length and width into a series of horizontal blocks, which are delineated by the main ore transport levels. Each block is sub-divided along the strike into smaller blocks, which are referred to as stopes.

The mining sequence in each ore source starts at the centre stope on the uppermost working level and progresses along strike towards the extremities. A series of blocks (faces) on each wing are mined simultaneously, but in echelon, so that the upper faces are always in advance of those on a lower elevation. This is termed the mining profile (Fig. 1).

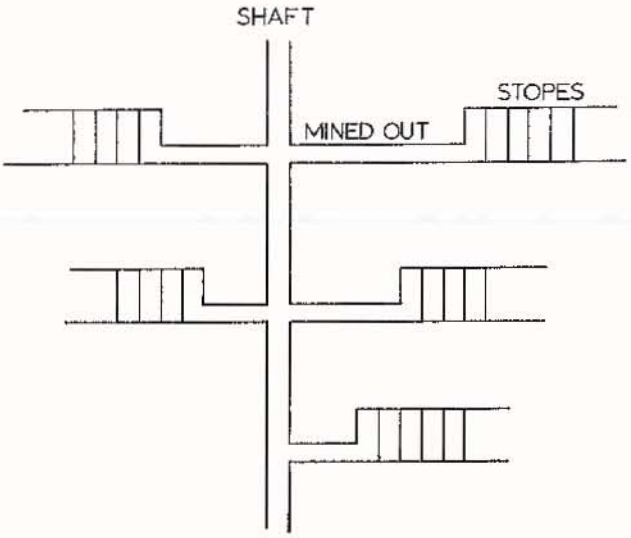

Fig. 1.

INITIAL INVESTIGATIONS

There were three areas in which it appeared possible to provide assistance:

(i) *Clerical.* At the largest of the shafts there could be up to 20 production faces, each face mining up to 10 stopes in a year. A large clerical effort is required, therefore,

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in the simple arithmetic of calculating true tonnages, grades of stopes and quantities of copper (and cobalt) produced. The manual work can be reduced by computerizing the calculations.Computerization can be also of great advantage in the later stages of planning, when a minor change to the early part of the plan requires the repetition of most calculations.

(ii) *General structure of the schedule.* In producing an initial schedule for discussion, trial and error methods must be used to obtain a schedule which satisfies all the constraints and enables the necessary copper output to be attained. It seemed possible to devise a method of producing this initial schedule by computer.

(iii) *Amendments to the schedule.* Amendments to the schedule are required for the reasons already mentioned. When the schedule is produced manually the number of amendments is kept as low as possible because of the amount of work involved. Initial indications showed that amending a schedule produced by the computerized system could be done with minimal effort.

A great deal of thought was given during the initial stages of the work to an attempt to define what is meant by a 'good' schedule.

The original aim was to devise a system which would produce the 'best' possible schedule with as little effort as possible. After much discussion it was found impossible to define precisely the qualities of a 'good' schedule. However, it was considered that if the system made planning considerably easier, the planner would be able to investigate a wide range of possible alternatives from which he could select the 'best'. Thus, although the optimum would not necessarily be achieved, a significant improvement could be envisaged over the current manual method.

Of the three shafts operated by the Rokana Division, Mindola is the largest and requires more calculation in planning than the other two shafts. In addition, the mining pattern at Mindola is much simpler and, therefore, more likely to be amenable to a 'mechanical' planning system. As the Mine Planning Department considered that a system which perhaps could be applied only to Mindola shaft would be of great value, the initial work was concentrated on this shaft.

MINING CONSTRAINTS

The uniform nature of the orebody at Mindola shaft leads to a simple mining pattern. Figure 1 is a schematic section through the mine parallel to the orebody.

General mining constraints which had to be met were:

(i) *Hoisting capacity.* All ore is delivered to the bottom of the shaft systems via ore passes and is then hoisted to the surface. Therefore the combined ore tonnage from all production faces is subject to an upper limit (that is, the hoisting capacity).

(ii) *Tramming capacities.* For a variety of reasons, there is an upper limit on the amount of ore which can be taken from any face in a given time period. In addition, there is usually a lower limit on the tramming rate.

(iii) *Profile constraints.* As mentioned previously, it is necessary to keep a production face at least a certain minimum distance 'ahead' of the face on the level immediately below. The word 'ahead' is used in the context of 'further from the shaft'. Faces on opposite sides of the shaft are completely independent.

(iv) *Manpower requirements.* It is not possible to frame specific rules to ensure that manning considerations are met. In general, however, it was considered that if the computer schedule ensured as little fluctuation as possible in the general scheme of mining, the mine planner could ensure that the schedule would meet manpower constraints.

PRODUCING THE SCHEDULE

The first attempt at a method of solution to the problem was a heuristic computer program. It was considered that this program could be incorporated easily into a user system. After a few months' development, problems were still arising and this method of solution was abandoned in favour of linear programming (L.P.) approach.

To be able to use precise information on quantities of copper produced from given quantities of ore mined, it is necessary to include full details of every stope which could possibly be mined. While this is possible, treating the stopes at each face as a set of separable variables, the size of the L.P. could well cause problems, particularly as most of the columns would be separable variables.

Although the objective of the schedule is set in terms of copper tonnages, the constraints which must be met are all given in terms of ore tonnage. It was decided, therefore, to formulate the L.P. in terms of ore mined where the copper constraint was included by using the average grade of each face. This approximation was found to be sufficiently accurate in practice.

THE LINEAR PROGRAM

The typical basic variable (column) denoted ORE(I,J) is the amount of ore to be mined from face I in month J.

Ore target

For each month a required tonnage of ore is set for the whole mine:

$$\sum_I \mathrm{ORE}(I,J) = T_J \text{ for all } J$$

The hoisting constraint is always satisfied if T_J is less than the hoisting capacity.

Ore limits

$$\sum_J \mathrm{ORE}(I,J) \leqslant L_I$$

It may be necessary to limit the amount of ore taken from any face if, for example, ore reserves are limited.

Profile constraints

An initial computer program calculates the average distance each face advances per unit quantity of ore mined, say F_I.

Then, after month N, the tonnage mined on level I is

$$\sum_{J=1}^{N} \mathrm{ORE}(I,J)$$

and, therefore, the face will have progressed a distance

$$D_I = F_I \times \sum_{J=1}^{N} \mathrm{ORE}(I,J)$$

The face immediately below [face $(I + 1)$] will have progressed

$$D_{I+1} = F_{I+1} \times \sum_{J=1}^{N} \mathrm{ORE}(I+1, J)$$

If the original distance between the faces was G_I, after month N the distance will be

$$G_I + D_I - D_{I+1} \geqslant P_I,$$

if P_I is the given minimum distance.

In the L.P. a profile constraint is present between every face and the succeeding face, assuming that the uppermost face is listed first. Sometimes there is no constraint, for example, the faces on the north side of the shaft are completely independent of the faces on the south side. Consequently, as no profile is required between the last face on the north side and the first face on the south side, the relevant P_I is given a large negative value which removes the constraint effectively.

Tramming limits

Upper and lower limits are given for every ORE(I,J) appearing in the Bounds Section of the L.P.

Total copper

In general, the upper and lower tramming limits are not greatly different and so it is possible to obtain a good estimate of the total amount of ore to be mined from any face over the whole year by taking the average of the upper and lower limits. From this estimate and the ore reserve information fed into the planning system, it is possible to calculate an average copper grade for each level.

A row in the L.P. then calculates the approximate total copper by multiplying each ORE(I,J) by the average grade for face I and summing over all I, J.

Although the copper grade at a face varies from stope to stope, a very good approximation is obtained by taking the average grade of the approximate amount of ore to be mined.

Objective function

As no single criterion could be found to describe a good schedule, the objective function was used to remove as much as possible of the month to month fluctuations in mining tonnage, for each face.

In the above notation the objective function is:

$$\sum_{I} \sum_{J=1}^{12} |\mathrm{ORE}(I,J) - \mathrm{ORE}(I,J-1)|$$

In this summation ORE(I,0) was given the value of the mining rate expected in the month preceding the first month of the new schedule. In this way a significant difference was avoided between the previous year's schedule and that for the succeeding year (that is, the schedule being calculated).

THE OVERALL SYSTEM

As it was planned to write computer programs to handle as much as possible of the arithmetical calculations, it was decided to produce a comprehensive computer system which would accept the user's data set out in a meaningful format, pass it to the L.P. package program and then produce a detailed production schedule.

Data entry and checking

To avoid possible problems in card sequencing, data are entered in any order and then sorted according to certain data fields. The program first checks for errors which prohibit the full completion of the job and then prints the necessary error messages. A severe error will not prohibit further data checking, but in this case no schedule is produced.

Where possible, the program checks the values of certain entries against pre-set limits and if the value is outside these limits a warning message is printed but the run is not aborted.

Matrix modifications

Revisions of the permanently-stored master matrix are calculated from the input data and stored on file for use in the linear program.

Linear program

The master matrix is revised and the solution to the L.P. is produced by the standard L.P. package program for interrogation by a subsequent program.

Detailed production schedule

A program reads from file the solution given by the L.P. package, produces a summary table and, using ore reserve data already stored, calculates the detailed schedule. A typical part of this schedule is shown in Fig. 2.

DETAILED PLAN MINE MINDOLA RUN 2

PERIOD 1

FACE		BLOCK NO.	CU GRADE	CO GRADE	ESTIMATED CU GRADE	TONNAGE	TONS COPPER	TONS COBALT
1880	N	N9080	2.34	0.09	1.87	4,000	75	3.6
1880	N	N9130	2.33	0.08	1.86	2,000	37	1.6
1881	N	N8980	2.01	0.06	1.71	5,000	86	3.0
2130	N	N8620	2.07	0.11	1.76	4,000	70	4.4
2130	N	N8665	1.94	0.11	1.65	2,000	33	2.2
2131	N	N8575	1.45	0.05	1.30	4,000	52	2.0
2380	N	N8305	1.57	0.05	1.26	5,000	63	2.5
2381	N	N8260	1.21	0.04	0.97	4,000	39	1.6
2880	N	N5840	1.82	0.16	1.36	10,000	136	16.0
2880	N	N5880	1.69	0.13	1.27	15,000	191	19.5
3140	N	N4240	1.80	0.15	1.53	7,000	107	10.5

Fig. 2.

Further runs

Amendments to schedules are achieved by submitting only the changed data. As the original data are stored permanently, amended runs can be produced at any time.

CONCLUSIONS

The computer system has been very successful in producing schedules for the Mindola shaft. Application of the system to the other two Rokana shafts has been less effective because of their much smaller size and the complicated mining sequencing caused by folding of the orebody.

Current use of the system has suggested a number of minor improvements which can be made easily. In the longer term it would seem quite possible to tie in the planning system with a computer ore reserve system now under consideration. In the even longer term it is obvious that the planning system would benefit greatly from the introduction of remote terminals.

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