Long-Term Mine Production Scheduling

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SYNOPSIS

A system has been developed to simulate the mining of the Mufulira orebody. The main output from the system is a picturegram from which the start date and effective life of all proposed mining faces can be measured. This information provides schedule dates for the completion of major capital development projects and stope preparation activities.

The orebody must be divided horizontally into main levels and vertically into blocks of equal interval. Ore reserves are defined by specifying the tonnage contained in each block and main level. Mining faces are defined by their co-ordinates, and may themselves be split into sublevels. The simulation maintains an echelon between contiguous sublevels. Other face parameters control the speed of mining, the availability and relative priority of the face.

The required production from each crusher/shaft system is specified. The technique of simulating the mining process in order to achieve the required production is described.

INTRODUCTION

A system has been developed to enable the planning engineer to evaluate the effects of a hypothetical production plan. The sort of effects which the system helps to determine are:

(a) Can the required production (crushed ore to surface) be achieved throughout the life of the mine?

(b) What is the life of the mine?

(c) At what date must new crusher systems and hoisting facilities be complete?

(d) When must major development be complete so that stope preparation of individual mining faces may begin?

By varying certain face parameters such as capacity, availability and priority, the planning engineer can generate a different production schedule whose effects may be more or less desirable than the previous schedule. This process continues until a schedule is produced, the effects of which are agreed to be the best that can be achieved, according to some management-specified criteria.

At the time of writing, the system has been developed to cater only for the Mufulira orebody in Zambia. Certain improvements which are described later will be incorporated into the system. At the same time the system will be written in such a manner that it can be applied to any orebody with similar scheduling characteristics.

SCHEDULING REQUIREMENTS

The orebody at Mufulira is split horizontally into main levels at intervals of 250 ft, and vertically into blocks of 200 ft width. A mining face is defined by its co-ordinates within the local block and main level numbering system. A mining face may occur on only one main level and may span two or more blocks. For example, a face may be defined on the 2 100 ft level between blocks 8 and 14. This face comprises all the ore that occurs on the 2 100 ft level between blocks 8 and 14 inclusive. As the width of the orebody changes continuously, the total tonnage of ore in block 8 may be significantly different from that in block 9. Metrication has resulted in a redefinition of main level and block intervals, but all examples in this paper will refer to the old block numbering system.

The mining face may itself be split horizontally into two or more sublevels. All mining methods in use in Mufulira require that a certain echelon is maintained when working along contiguous sublevels. The requirement is simply that the block advance along the top sublevel should be greater by some fixed minimum distance than the second sublevel, and that mining along the second sublevel should have progressed further than the third, and so on. For convenience, the fixed minimum distance used by the system is exactly one block interval, that is, 200 ft. In practice, it may be acceptable for a much narrower echelon to be worked. If the system is presented with a partially-mined face whose block advance on each sublevel differs from the ideal, it will maintain the echelon actually existing at the start of the plan, during the remaining life of the face.

CRUSHER/HOISTING FACILITIES

The planning engineer specifies the required production not on a mine basis, but for each individual crusher and shaft system. At Mufulira there has so far been no requirement to cater for more than three underground crusher/shaft systems simultaneously. (The terms 'shaft' and 'crusher' are used synonymously, while 'call' is taken to mean the required monthly production from any given shaft).

It was originally considered that the scheduling for each shaft could take place independently with no communication of data between the shafts. This was achieved by nominating the shaft to which the ore from each face would be sent, and then running three separate schedules in series. This over-simplification became an embarrassment during operational use of the system. It was modified, therefore, to allow any face to change arbitrarily the shaft to which it sends its ore.

SPECIFYING THE PRODUCTION PLAN

In order to propose a hypothetical production plan, the planning engineer will need to specify the ore reserve tonnages, the mining faces from which ore may be extracted, and the required production from each shaft throughout the life of the plan.

Ore reserves are specified to the system by means of a file of cards indicating the tonnage of ore contained in each block on each main level. These cards are computer-generated. There may be several cards for the same block and main level as the system which produces these cards estimates tonnages by orebody type. Copper grade is available for each block but no use is made of this information at present. The system simply aggregates the tonnage within each block and main level and assumes zero tonnage in all other blocks. No attempt is made to mine a part of the orebody where no mining face has been defined. The system picks up the actual remaining tonnage of faces already in production from data supplied for these faces. Thus, only additional geological data need modify the ore reserve file.

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For each mining face the planning engineer must specify its co-ordinates (main level, start block and end block), the shaft to which its ore is sent, and the rate at which it will be mined, that is, the *capacity* attribute. He must also specify the number of sublevels into which it is to be split. An extraction factor, appropriate to the mining method to be employed, is required in order to convert the block tonnage into the effective tonnage available on each sublevel. If the face is already in production at the start of the plan, the block advance and percentage mined on each operating sublevel are required. The planning engineer may wish to control the availability of the face, that is, the date on which he estimates mining may commence. When total available capacity exceeds the shaft call, the planning engineer will need to influence the selection of faces whose mining is to be slowed or stopped so as to avoid overproduction. These two concepts, availability and urgency, are catered for by specifying a vector of *priority* values and a series of dates which control the time at which the new priority takes effect. A priority of zero indicates that the face is unavailable for mining. The higher a positive priority value, the more readily will the face be selected for delay, when the possibility of overproduction arises.

The required production from each shaft is specified as a total monthly tonnage of crushed ore to surface. At present the system allows eight dated changes to the call of each shaft throughout the life of the plan.

ATTRIBUTE VARIABLES

Before describing how the system actually simulates the mining of the orebody, it is necessary to define certain conventions and generic names which refer to the attributes of a face during its life. The system makes use of a 'time-now clock' and the values of the attribute variables change as time advances. The time increment for scheduling purposes is one month.

A face has a *status* attribute which indicates what stage in its life it has reached. When mining has started, and some but not all of its sublevels are producing ore, it has status 'S'. This situation is illustrated in Fig. 1(a) for a face with five sublevels spanning blocks 8 to 14. The shaded portion represents that part of the face that has been mined. As soon as mining commences on the lowest sublevel, the status changes to 'O' provided all sublevels are still operating, Fig. 1(b), and the face is then producing ore at its maximum capacity. As soon as the top sublevel is completely mined and providing the lowest sublevel is at least partially mined, the status changes to 'E' The face is now producing ore below its maximum fully operating capacity, Fig. 1(c). If, however, a face is defined with more sublevels than blocks, then the one-block echelon rule will prevent it from ever producing ore from all sublevels simultaneously. This situation is illustrated in Fig. 1(d). Although the top sublevel has been mined completely, mining has not yet started on the two lowest sublevels. Status 'X' is used to define this condition and the face will retain this status until mining commences on sublevel 7. Virgin and fully-mined faces have status 'N' and status 'F', respectively. It follows that the chronological order of face status will normally be 'N', 'S', 'O', 'E' and 'F', but if the face has more sublevels than blocks the order will be 'N', 'S', 'X', 'E' and 'F'.

A face has a *capacity* attribute which will be the maximum tonnage of ore which it may produce in one month. The capacity at any point in time depends on the status of the face and the number of active sublevels at that time. The nominal capacity defined by the planning engineer is the tonnage which may be produced when all sublevels are operating. For any other status the actual capacity will be less than this amount.

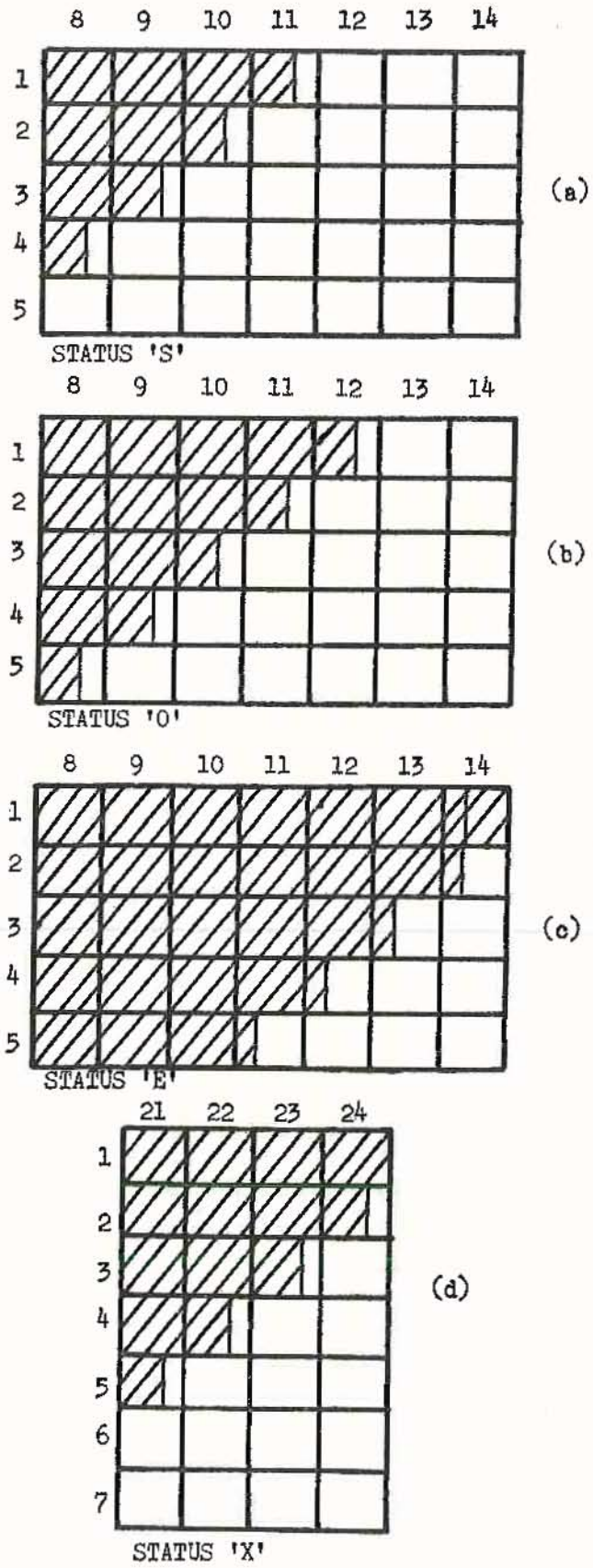

Fig. 1

Let k be the nominal capacity, n the number of sublevels in the face, s the number of sublevels operating at the start of the month and t the proportion of the nominal capacity normally available, that is, $t = ks/n$. Also, let p be the remaining tonnage which can be mined without having to introduce a new sublevel (applicable to status 'S' faces), q the remaining tonnage which can be mined without losing a sublevel (applicable to status 'E' faces) and r the total remaining tonnage in the face, With these notations the formulae for capacity are as follows:

If *status* = 'S' and $p \geqslant t$, then *capacity* $= t$.

If *status* = 'S' and $p < t$, then *capacity* $= k[s + (1 - p/t)]/n$.

If *status* = 'O' then *capacity* $= k$, unless mining has already advanced to the end block of the face. In this latter case the formula for status 'E' is used.

If *status* = 'E' and $q \geqslant t$, then *capacity* $= t$.

If *status* = 'E' and $q < t$, then *capacity* $= k[s + (q/t - 1)]/n$, unless this quantity is greater than r, in which case *capacity* $= r$.

If *status* = 'X', then *capacity* $= t$.

The capacity calculations can be explained by considering that when the number of active sublevels does not change during the month, the actual capacity is always the simple ratio ks/n. When a new sublevel is introduced during the month some allowance must be made for the proportion of time spent at the new increased operating capacity. Similar reasoning applies when the uniform rate of advance results in a sublevel being lost, that is, completely mined out during the month. In the case of status 'X' faces, the one-block echelon rule clearly restricts the maximum number of active sublevels to the number of blocks spanned by the face.

The *inblock* attribute records the number of the block to which mining has advanced on each sublevel of the face.

The *remtons* attribute records the tonnage remaining in the current block (inblock) on each sublevel. *Remtons* is reduced progressively as the simulation process mines through the current block, until it reduces to zero when an 'end-of-block' condition is reached.

The *slsoping* attribute records, for each face, the number of sublevels producing ore at any point in time.

The *cuprty* attribute contains the current value of the face priority.

MAIN SCHEDULING LOGIC

The steps of the main scheduling logic are discussed now in some detail.

Step 1. The ore reserve data, face definition data and production call data are read and validated. Face definition cards are read in the same order as the preferred mining sequence of the faces in each shaft.

Step 2. The system apportions the total ore reserves in the blocks bounded by each face to the sublevels of the face, and then multiplies by the extraction factor supplied. For all faces actually in production at the start of the plan, the system calculates the value of the *remtons* attribute on each sublevel, and sets the sublevel tonnage in all preceding blocks to zero. The 'time-now clock' is set equal to the start date of the schedule, and the current value of the face priorities and shaft calls are referenced.

Step 3. The capacity of all current faces is calculated and aggregated by shaft. The scheduled production of each face is set equal to its available capacity. This action is taken in the expectation that the total capacity will not exceed the required call, that is, the speed at which current faces are being mined will not need to be reduced.

Step 4. The total available capacity is compared with the required call. If the capacity lies within one per cent of the call then the decision about how much each face should produce has been reached and mining of all current faces can proceed at maximum rate. If the capacity exceeds 101 per cent of the call, then one or more faces will have to be slowed or stopped temporarily (Step 6). If the available capacity is less than 99 per cent of the call, then a search must be made to see if there are any virgin faces yet available (with non-zero priority), whose introduction would not break the undermining rules of the mining method in use.

Step 5. The system looks at the remaining virgin faces defined for this shaft in the order in which they were read into the system, that is, in the preferred mining sequence. If it finds no face available it simply transfers control to Step 7 and accepts that the required call cannot be met this month. If it finds an available face whose introduction passes the undermining check, it sets its *status* to 'S', calculates its initial capacity, adds its capacity to the shaft total and returns to Step 4 for a new comparison. If the system is introducing this face out of the preferred mining sequence, because 'earlier' faces failed the undermining checks, warning messages are printed on the scheduling log.

Step 6. In this situation the available capacity has built up beyond the required production. The system notes the amount by which the capacity exceeds the call. The problem is simply to reduce the rate of mining of the most convenient face. The selected face has its scheduled production reduced by the amount by which the total capacity exceeds the call. If production from the selected face is completely stopped, and the total shaft capacity still exceeds the call, then more than one face must be selected. Status 'S' faces are always selected in preference to status 'O' or 'X' faces. Within any status type, the face with the numerically highest current priority is selected first.

Step 7. Having decided exactly what tonnage will be extracted from each face in the month under consideration, the system prints a list of the face names, their available capacities and their scheduled production rates. Any face producing below capacity is annotated '*'. Any shaft whose call cannot be met is annotated '**'. Figure 2 illustrates an extract from a hypothetical scheduling log.

SCHEDULING LOG FOR NOVEMBER, 1999.

SHAFT 1	CALL:	800 000	PRODUCTION:	540 000**
75 FACE 32	CAPACITY:	240 000	PROD:	240 000
75 FACE 35		120 000		120 000
75 FACE 36		120 000		120 000
75 FACE 38		60 000		60 000
75 Face 39 has been stopped to prevent undermining block 789.				
SHAFT 2	CALL:	900 000	PRODUCTION:	900 000
72 FACE 16	CAPACITY:	130 792	PROD:	0*
72 FACE 18		300 000		300 000
75 FACE 19		240 000		60 000
75 FACE 20		240 000		240 000
75 FACE 21		300 000		300 000
SHAFT 3	CALL:	500 000	PRODUCTION:	500 000
75 FACE 33	CAPACITY:	200 000	PROD:	200 000
67 FACE 51		150 000		150 000
72 FACE 52		120 000		120 000
75 FACE 55		60 000		30 000*
75 Face 53 cannot be started due to undermining.				
75 Face 54 cannot be started due to undermining.				

Fig. 2. Extract from scheduling log.

In shaft 1 the system is unable to produce the required call. A contributory factor is obviously the temporary cessation of face 39 on the 7 500 ft level. The system was unable to introduce any new faces, probably due to their non-availability.

In shaft 2 the total capacity available exceeds the required production. Face 16 has been stopped altogether while the rate of mining face 19 has been quartered.

In shaft 3 the total capacity available at the start of the month was short by 30 000 tons. The system had to introduce face 55 at half of its initial status 'S' capacity. The system prints messages to warn that this face is being introduced out of sequence.

Step 8. The next task is to mine the actual production from each face. The procedures which the system uses to simulate the mining process are different for each status type but certain principles are common to all. The system advances in discrete steps along each sublevel by subtracting one per cent of the sublevel tonnage of the relevant block from the *remtons* attribute of that sublevel. By proceeding in small steps along each operating sublevel by an amount proportional to the tonnage in the relevant block, the system maintains a perfect echelon and ensures a uniform rate of advance. At the end of each iteration, that is, when a one per cent advance has just been made on the lowest operating sublevel, the system compares the total amount mined with the scheduled production to determine the need to continue. Any excess in the amount mined is re-apportioned to the *remtons* attribute of the operating sublevels.

When an end-of-block condition is reached on any sublevel, the action taken by the system depends on the status of the face and on the sublevel concerned. If mining has not yet advanced to the end block of the face, it is always possible to advance into a new block. If the end-of-block condition has been reached on the lowest operating sublevel in the start block of the face, and the status is still 'S', then the system can additionally introduce a new sublevel. The maintenance of attribute variables enables the system to 'see' what state has been reached, and to decide what action can be taken, simulating the real process absolutely. The system uses separate logic for mining each status type. It has been found that when an unreasonably high capacity is specified for a fringe area of low reserves, a face may undergo more than one status change during a single month.

Step 9. The task here is to increment the time-now clock and establish the new face priorities and the required production of each shaft. Each face is checked to see if it could advance into a block where reserves still exist on the main level above. If the possible undermining is not permitted for the mining method in use, the system makes the face temporarily unavailable.

Step 10. The system checks to see if all reserves have been fully mined out before returning to Step 3 to schedule next month's production. Scheduling can also be terminated when a given number of years have elapsed from the start date of the schedule.

Step 11. The final output from the system takes the form of a picturegram which shows which blocks produce ore on each main level throughout the life of the schedule. The block numbers of the orebody are represented by the vertical axis. Time is represented on the horizontal axis with two print positions per month. On this scale a full 25-year schedule will generate a picturegram 60 in. in width. It is impossible to fully assimilate the 'effects' of a schedule without examining the complete picturegram, but for purposes of illustration a small extract from a hypothetical schedule is shown in Fig. 3.

A two-digit main level code is printed against the appropriate block number and month to show that ore will be extracted from this main level and block at the time indicated. For example, in January 1998 ore will be extracted from blocks 409 to 413 on the 5 250 ft level and from blocks 400 to 402 and 404 to 407 on the 5 500 ft level. There is a face on the 5 750 ft level starting in September 1998 from block 403 mined from west to east. In January 1999 it briefly advances into block 401, but it is suspended by the system for three months, until block 401 is fully mined on the 5 500 ft level. It is stopped for a similar reason in August 1999. Another face on the 5 750 ft level starts from block 404 in April 1999. The face on the 5 250 ft level obviously terminates at block 417, and is near the end of its life by November 1999, as it has only three blocks active at this stage. The figures at the bottom of the picturegram would show the total monthly production in each shaft, together with a mine total.

With a complete picturegram, it is a simple matter to look up the start date and effective life of any mining face, and to visualize the interaction of the constraining factors in the scheduling process.

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399
400  55555555555555555555555555555555555555755555555
401  5555555555555555555555555755555555575757     .
402  5555555555555555  . 575757     . 575757     .
403  I     .     .  5757575757     . 575757     .
404  55555555555555     .     I     5757575757575757
405  555555555555555555555  I     .     5757575757
406  5555555555555555555555555555555     .     5757
407  555555555555555555555555555555555555555555.
408  I 555555555555555555555555555555555555555555555
409  525252.     555555555555555555555555555555555
410  52525252525252     . 555555555555555555555555555
411  5252525252525252525252521     . 55555555555555
412  525252525252525252525252525252     .     .
413  5252525252525252525252525252525252525252     .
414  I 52525252525252525252525252525252525252525252
415  I     .     525252525252525252525252525252525252
416  I     .     .     . 52525252525252525252525252
417  I     .     .     .     I     5252525252525252
418  I     .     .     .     I     .     .     .
     I.......................I.....................
     IJFMAMJJASONDIJFMAMJJASON
                    I
          1998                1999
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Production in 1 000 tonnes per month.

SHAFT 1 xxx xxx xxx xxx xxx xxx xxx xxx xxx xxx xxx
xxx xxx xxx xxx xxx xxx xxx xxx xxx xxx

Fig. 3

IMPROVING THE SYSTEM

It would be far easier to interpret the picturegram if it could be printed in three dimensions with each main level on a different plane. Current experience has shown it to be useful to colour each bank of main level codes with a unique colour and to mark the boundaries of each mining face on the picturegram. If there are only a few main levels it is quite practical to print separate sheets showing only the blocks active on one main level at a time. By arranging these sheets in regularly-spaced parallel planes, it is possible to get a rough idea of the shape of the orebody and, at the same time, an accurate idea of the time at which any part of the orebody will be mined.

The system which has been described caters successfully for the requirements of long-term production scheduling at Mufulira. As the author is not a mining engineer, he is not qualified to guess what similarities occur in the scheduling of

other orebodies. The facility of ignoring copper grade when developing the schedule would seem to limit its applicability. Included in the planned modifications to the system is one which will calculate the pure copper content of each month's production by taking note of the grade of the blocks from which the ore has been extracted. An additional enhancement will allow slight over-production in one or two shafts, when it is not possible to achieve the required call from the third shaft.

It would probably be useful to plot a histogram of scheduled production in each shaft to get an idea of what variations in required call the orebody can tolerate.

OBSERVATIONS ON PRACTICAL USE

As a computer application the system has been well conceived. It solves many trivial calculations and logical decisions which would be impractical by conventional methods. A schedule covering 25 years takes less than one hour to simulate on a medium-sized computer. It is a simple matter for the engineer to adjust the capacities, availabilities, priorities and sequence of the mining faces, and so produce an improved schedule. It is equally easy to evaluate the possibility of varying the required production from each shaft and so reduce or extend the total life of the mine.

The information flow between geology, management aspirations, long-term production scheduling, capital project scheduling, major development scheduling and stope preparation scheduling is not 'uni-directional'. It is continuous with observations and decisions in one area, which affect decisions in all the others. Only by having a battery of systems which can perform the ore reserve estimation, scheduling and costing functions quickly, can management hope to maintain overall plans in a near-optimum state.

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