Chapter 74

AN EDP- MODEL OF OPEN PIT SHORT TERM PRODUCTION SCHEDULING OPTIMIZATION FOR STRATIFORM OREBODIES

by

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ABSTRACT

The best use of available reserves to give good metal recoveries relies on short term mine production scheduling. The aim is usually to produce a plan to guide mining in specific areas that will enable mine operations to deliver the budgeted tonnes and grade to the mill and keep within the long range mine plan. Thus, short term production scheduling is an important aspect of the open pit mine planning function.

Since the 60's increased attention has been paid to effective production scheduling as a means of improving the economic viability of existing mines. Hence, mine scheduling scheduling systems have been evolving rapidly during the last two decades. These systems include manual techniques, computer based simulation, mathematical programming and more recently Computer Aided Design (CAD). Some general draw-backs of the current scheduling systems are that firstly, the costs of acquiring and using them are not at all insignificant especially for small to medium sized pits. Secondly, there is an inherent trial-and-error aspect in these systems. Thirdly, they tend to be suited for specific orebody geometries, hence lacking the necessary generality. For instance, the use of computer programs for planning open pits to mine stratiform orebodies raises problems which are not usually met when massive orebodies are considered. There for, a need exists to develop simpler but effective short term pit scheduling procedures suitable for stratiform type orebodies, considering their geometry and geology.

This paper describes a PC- based model designed to assist the planning engineer in optimizing the short term production schedule in open pit mines with stratiform orebodies. The model is based on a combination of linear goal programming and deterministic mining simulation. The orebody model is made up of ore and waste mining regions where winning and ond/or stripping are taking place. These shovel regions form the basic planning elements in the model. This approach does not require the laborious preparation and use of a regular block model. The computer program consists of main modules: (i) Data capture - processes the raw data into the required format for mine planning. (ii) Precedence mining constraints - checks the status of each shovel region at the beginning of a given scheduling period with regard to geometrical mining constraints such as undercutting. (ii) LP- Optimization - provides an optimal selection of ore shovel regions which do not violet geometrical constraints for mining in the period, the objective being to maximize the contained metal equivalent in the blended R-O-M ore and at the same time to minimize deviations in grade and tonnage from the call values. (iv) Post LP- Simulation - enables the user to smooth out the LP solution in order to adjust it to a practically executable plan and simulates mining of ore and waste for the period. Shovel allocation to selected ore and waste shovel regions, unit operations and depletion of reserves are executed in this module. Preliminary testing of the model for monthly production scheduling using data from Nchanga OPen Pit on the Zambian Copperbelt indicates that it can be a useful planning tool and gives acceptable results.

INTRODUCTION

Since the introduction of technical computing in the minerals industry increased attention has been paid to effective production scheduling as means of improving the economic viability of existing open pit mines. Poorly generated production schedules can lead to adverse cash flows which can in turn threaten the very existence of the mine, especially during these times of depressed prices and marginal orebodies. In this regard, short term mine production scheduling has an important role to play because it is at this level of planning that the knowledge about the orebody and operating conditions are known with a higher degree of certainty. This schedule determines the locations within the pit where production should take place and at which rates , in order to satisfy demands in tonnage, composition and waste/ore ratios. Due to the relatively short duration of this schedule, results can be checked against actual performance and corrective measures taken.

Historically, short term production scheduling in open pits has been a manual task, but due to the large amount of data to be processed and the calculations that have to be performed to arrive at a schedule, computers are now routinely employed. Current methods for short term production scheduling in open pit mines can be conveniently divided into four broad categories: 1. The manual approach (Cousins, 1979), 2. Computerized scheduling based on simulation. Examples of these are: Fitzgerald (1977), and Edmiston (1988), 3. Mathematical programming techniques(Soukup, 1975, Wilke and Reimer, 1977, Gershon, 1982), 4. Computer aided scheduling: This method evidently reflects the state of the art in open pit planning incorporating the best features of manual and fully computerized scheduling. These systems allow the engineer to work in exactly the same manner as he would in a manual exercise but also take advantage of the speed and power of the computer by interactively controlling the process with the help of a graphics screen. Such integrated systems have been reported by Franklin (1985); Jardine and Evans (1989), Mellish et al (1987); Grady et al (1990), and Kear (1990).

Evidently, current approaches for open pit short term production scheduling are characterized by; (a) Inadequacy of the manual methods, (b) An inherent trial and error aspect of the simulation and CAD systems, (c) Limitations of solely optimizing techniques, (d) Significant application costs and complexity of integrated programms, and (e) Suited for specific orebody geometries. Available models have not been able to solve the problem of producing general production scheduling programs. In view of the above observations it is necessary to develop programs which tend to fill in the existing gaps in the use of computers in mine planning. The short term scheduling model described in this paper is based on a combination of simulation and an operations research technique. This approach makes it possible to realistically model the mine scheduling problem (Wilke,1987). Further, the emphasis should be on interactive, simple to use, flexible and cost effective PC- based programs. The model STOPPS(Short Term Optimum Pit Production Scheduling) utilizes a combination of linear goal programming whose objective functions are to maximize contained metal in R.O.M. ore and to minimize deviations in grade and tonnage and simulation which handles the remaining procedures and calculations of short term scheduling. Being interactive, it ensures that the engineer has the overall control of the scheduling process intervening where necessary if the computer generated result is not practical. The model is suitable for stratiform orebodies whose geometry and/or geology can prevent and have in the past prevented direct application of the currently available models. Even without a graphics capability, the simplicity of the model considerably enhances the effectiveness of the short term production scheduling function in open pit mines.

GENERAL OBJECTIVES OF OPEN PIT SHORT TERM PRODUCTION SCHEDULING

Mine production scheduling is conveniently broken into long term, medium term and short term, each with particular objectives and appropriate duration. The long range plan comprizes typically a longer period of time and is not very specifying in details(it involves long term investments and the necesary waste removal). The medium term plan indicates such things as haul roads, mining sequence, equipment investments, etc. Short term planning is at the tactical level.The short term production scheduling in this paper refers to a time frame of monthly planning at an operating open pit mine. Although it is clear that the details and objectives of short term planning are considerably different from those of long term planning, the short term plan should follow the long term plan. Short term scheduling in open pit mines is of utmost importance such that it should be modelled separately in order to consider all the factors.

Several objectives of the short term mine production scheduling are:

- Prediction of the next months ore quality (i.e,average grade) from the planned faces in the mine and the reliability of the prediction.
- Determination of the anticipated fluctuations in the daily grade (ore quality) around the estimated monthly grade.

- Within the constraints of the long term plan, indication of the exact locations of the ore, or the waste zones to be mined in the period, and at which rates, in order to satisfy demands on tonnage (mine call), composition of the run-of-mine (ROM) ore and waste/ore ratios, leading to an "optimum" mining sequence.
- Absolute deviations from stipulated quality requirements in the R-O-M ore have to be *minimized* since the variations in composition of the blended ore can affect mill recovery.
- Detailed allocation of mining equipment, for example, allocation of shovels to mining blocks, truck dispatching to different shovels, etc.
- Efficient utilization of open pit equipment and other resources.
- Ensure that the plan is flexible and is practically executable.

Among the objectives stated above, the first two can be achieved by using geostatistical tools, whereas the rest can be achieved by suitable operations research techniques such as linear programming in combination with simulation as is the case in the current model. The first two objectives are not dealt with in this model as it is being assumed that a suitable technique exists for assigning grades to blocks of ground.Clearly,an optimum schedule cannot be expected to be global since such a model would be fairly complicated to formulate and too large for efficient mine planning. The model STOPPS was conceived such that the linear goal programming part considers only the quality and quantity requirements of the schedule. The use of mega blocks simplifies the problem further and reduces on the potential size of the LP. The other procedures and computations related to short term production scheduling such as shovel allocation, geometrical constraints, etc, are handled by the simulation part of the model. The result is a powerful planning tool which considers the various aspects of short term production scheduling in sufficient detail. This modelling approach is justified due to following reasons:

(a) It is important to furnish as much ore of uniform grade and tonnage as the plant is capable of handling in order to ensure the plant's operating efficiency. This problem of blending ore from different locations in the pit can be easly formulated and solved using Linear Goal Programming.
(b) Successful application of Linear Programming calls for an ingenious formulation of the problem.
(c) The LP eliminates the trial-and-error aspect when selecting ore increments for analysis; the resulting selection is the best considering the available input values.
(d) Simulation is a very flexible technique which can effectively handle the variety of procedures and calculations of short term production scheduling.
(e) The modular approach implies that the program units function as independent procedures but sharing the input and computed results.

BRIEF DESCRIPTION OF THE STOPPS MODEL

General Considerations

The STOPPS model was conceived such that due consideration was given to the practical requirements of any computer assisted short term scheduling methodology. Primary among these requirements is that the system should be simple and easy to follow through, reflecting the same logical sequence one would follow when scheduling by hand. Recent experiences show that many integrated programs still take several weeks of direct training from vendors due to the complex procedures that have to be followed when using such systems.In this model simplicity is achieved by the program logic and interactive mine planning through selection of menu options, responses to querries posed by the system on the screen, and on line input of certain data items. Further, by the conception, it was realized that a global optimum solution would be impossible to achieve as this entails consideration of several variables. However, the need for utilizing some kind of optimization in a subproblem is very obvious, since there are normally several active faces in multi level open pit mine where mining is taking place and proper blending of ore from the different areas is usually the objective of the scheduling. So the approach adopted is to optimize at least the ore blending requirements. A special form of LP known as goal programming was employed for this purpose as will be shown later. This routine effectively removes the subjectivity associated with the selection of mining increments currently common in almost all CAD systems. The restriction of the LP algorithm to ore mining only is logical because this is where the crux of the problem lies. All other aspects and computations of short term scheduling are handled by the simulation part of the model. Further consideration was given to the problem of orebody representation. In view of the geometry of stratiform orebodies it was decided to use shovel regions as opposed to regular blocks as basic mine planning elements. As will be shown later, this aggregation results in considerable savings in terms of the computational effort. The model is capable of handling up to three mineral products in a pit.

Model of the open pit

Stratiform orebodies are characterized by relatively narrow widths(6-30 m) and generaly dipping at 20-30 degrees. The mineralization is usually stratified with areas near the footwall being richer, grades decreasing toward the hangingwall. Examples of well known stratiform orebodies are those found on the Zambian Copperbelt (Hoogeveen 1973) and Zaire with copper and cobalt as the main minerals. The use of computer programs for the design and evaluation of pits to mine stratiform orebodies raises problems that are not usually met when masssive deposits are considered. For example, it is essential to represent the thin orebodies in considerable detail, but the higher stripping ratio implies that a large amount of homogenious overburden is also represented in the same detail, with attendant problems of preparation of geological data and computer storage. To obtain a clear representation of the fairly thin strata, it would necessary to use a small block size. However, a horizontal section through such an orebody at any level would show that on the average less than 20 % of the resulting total block matrix lies in the ore horizons. The remainder of the matrix will consist of large areas of undifferentiated waste. It appears then that in this case a regular block model is inappropriate and has little practical use with regard to short term production scheduling. It was thus decided to model the pit as a system of shovel regions where winning and/or stripping are taking place (Figure 1). These shovel regions and are considerd fixed during the planning period. The direction of face advance and rules for setting up shovel regions are determined acording to practical requirements of open pit mining. The various grade zones are marked out on the plan and can used as a guide when determining the sequence of the blasts or demarcation of areas for mining in the short term planning period.

Three types of shovel regions can be identified for easier handling in the computer program, namely those lying in the ore zones, waste zones, and ore-waste boundaries (this could be at the footwall or hangingwall etc). This distinction is fully exploited in the computer program as certain computations apply only to certain types of regions. For example, while the simulation part of the model considers all three types of shovel regions, the LP part is restricted to shovel regions in ore zones of the orebody.

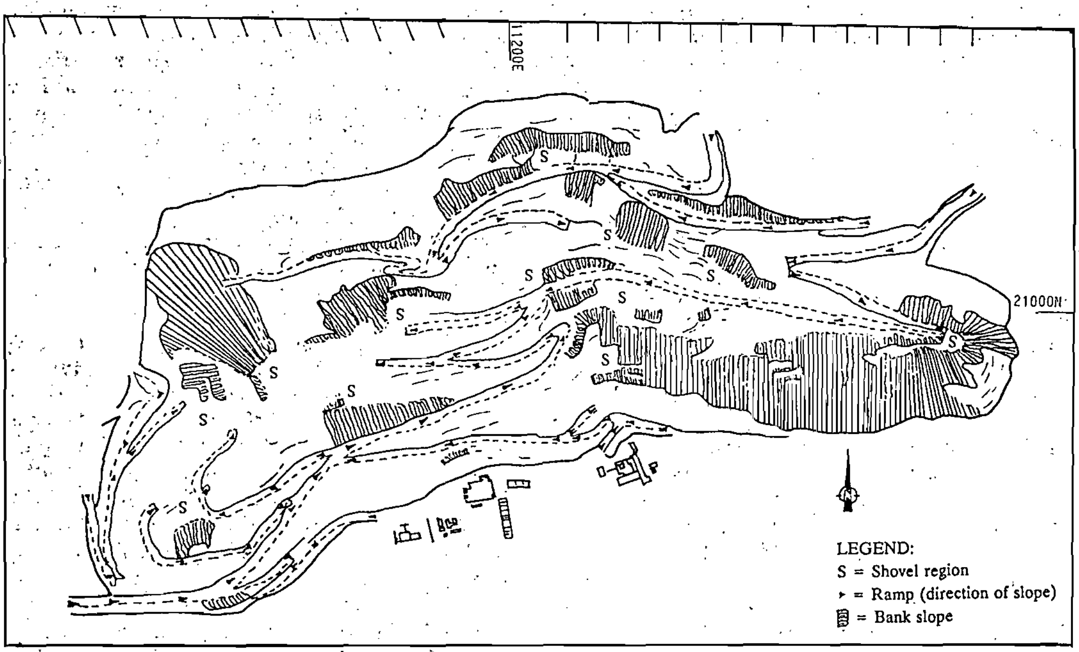

FIGURE 1. Model of the open pit as a system of shovel regions.

Components of the computer program

Figure 2 shows a schematic flow chart of the STOPPS model. The computer program essentially consists of four main modules: Data capture, pre- LP simulation, LP selection, and post- LP simulation. The modules and submodules reflect the different tasks of short term production scheduling in open pit mines. The program is written in Fortran 77 and implemented on a PC (IBM PS/2), but can be run on any compatible PC with minimum 640 KB RAM, mathematical Coprocessor and a Printer. The functions of each module will be briefly discussed:

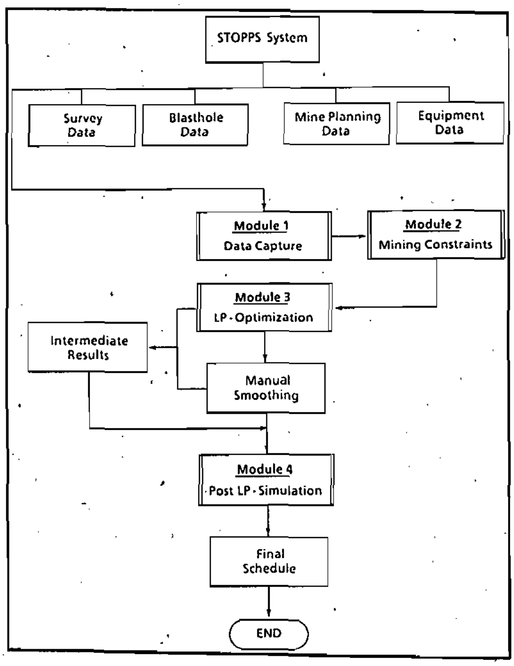

FIGURE 1. Schematic flow chart of the STOPPS model

1. Data Capture: The required input to the program include data from open pit surveys, blasthole data,equipment data and pertinent mine planning information. The survey data is used to demarcate the boundaries of shovel regions and areas for mining in the period, location of bench faces, etc. Thus, each shovel region or a portion thereof can be stored as a series of pairs of coordinates of the corner points as seen on the plan. The extent and size of the shovel regions depend largely on grade zones on a particular bench level as well the production requirements. The amount of ore or waste in each shovel region or part of it can then be easily computed. The change in location of bench faces due to mining advance can be automatically updated in the program but the new polygon boundaries have to effected by editing the relevant data file. Either, blasthole data or core drill data is used for quality parameters depending on their availability. Equipment data mainly includes shovel capacities, fleet size, cycle times and elements of availability. Mine planning data include general information such as bounds on grades and tonnage, operating strategies, etc. The function of this program module is to process the raw data into the figures required for production scheduling. For example, grades are converted to a figure called "specific metal equivalent" which constitutes the objective function coefficients in the LP.

2. Mining Constraints: As mentioned earlier, the optimizing routine does not take into account practical - constraints characteristic of open pit mining. These constraints are mainly geometrical and apply to both ore and waste shovel regions. At the end of each planning period, the physical situation in the pit is obviously subject to change as mining faces have advanced due to removal of blocks of ground. Stripping obligations, ramp access, etc, also change accordingly. Hence, it is important to check the status of each shovel region at the beginning of a new period in order to ensure that certain requirements are met before proceeding with the scheduling. This saves a lot of computational effort because only shovel regions deserving attention are scrutinized.

In this module four practical mining constraints are considered, namely working room, undercutting or slope angle requirements, accessibility and stripping ratio. Checking whether a shovel region has enough working room or not is important otherwise it would not be possible to station and operate mining equipment efficiently. To do this the program calculates the difference in coordinates between the toe line and the crest line at the mining front taking into account shovel cut and berm widths and then compares this to the required minimum working room. Undercutting is not permitted and can be avoided by observing the slope requirements. This is done by compairing the diameters of imaginary lines drawn across the pit connecting the bench midpoints of opposite lying faces for any two consecutive levels. Stepwise mining ensures that the diameter for the upper level should be greater than that of the following lower level, if not then mining of the lower level would violate the slope constraints and should be avoided until the upper face or a part thereof has been extracted. The result of this module is a set of shovel regions which satisfy the practical mining constraints and hence, can be considered for scheduling in the next period. This approach differs from previous methods,for example, Wilke and Reimer (1977) whereby the checking is done after the LP routine has been executed. The one disadvantage of this earlier method is that it leads to increased computational effort as blocks beyond reach are also taken into account.

3. LP Optimization: This routine is has the task of selecting ore shovel regions which should be mined in the next period so that the tonnage and grade requirements can be satisfied. Only shovel regions not violating the practical mining constraints are considered here. It is assumed that the reader is familiar with the methodology of linear goal programming as theoretical details will not be considered in this paper. Interested readers are referred to Charnes and Cooper (1961) for further details. Nevertheless, the formulation of the LP as employed in this model is given in Appendix 1. Here the decision variable (X_i) denotes the (unknown) amount of ore to be mined from shovel region i in the period under consideration. This aggregation significantly reduces on the potential number of decision variables in the Linear Programm.

The objective function is to maximize the metal content in the R-O-M ore, obtained by multiplying the average grade of a shovel region by ore tonnage. This optimization criteria reflects the long term strategy to mine high grade areas first so as to recoup the investment early in the life of the mine and/or take advantage of the higher metal prices on the world market. Apart from stipulating the lower und upper bounds on quality parameters and tonnage, management usually desires that the quality of each parameter be as close as possible to the required average grade in the R-O-M ore for optimum plant operating efficiency. Thus, in the goal programming formulation of the scheduling problem, there is a simultanious goal in the objective function, namely the minimization of absolute deviation of each quality parameter from its required value.

The solution of the LP system constitutes values of Xi which will make the resulting deviations as small as possible. The simplex algorithm was used to solve the system. By changing the values of the nonnegative weights W_k, the user can manipulate the degree of deviation of each parameter. A weighting factor of zero for any parameter would imply that the deviation of this parameter is within acceptable limits. One practical application of these deviations is the assessment of incurred penalties or mill charges for every unit that the mill feed grade is below or above a specified value. Hence, changes in the uniformity (in terms of both grade and tonnage) can lead to an increase in the total operating cost.

4. Post LP Simulation: Assuming that the LP module is successfully executed and gives an acceptable solution, the next step is to simulate the actual mining process during the period under consideration. This is done in the post LP simulation module which consists of several routines to handle the various mine planning tasks. The short term production schedule must also allocate each individual shovel to specific mining faces. Considering the fact that a typical pit has several shovels of different types and sizes not to mention the number of active faces at any given time, the problem of shovel allocation can be very complex. In the STOPPS model allocation of shovels to working areas is done heuristically by simply considering shovel productivities per unit of time and the tonnage to be moved from each face. This leads to a "capacity:production" ratio as a criterion for routine allocation of shovels. The computer considers all the available shovels in the pit and compares their productivities with tonnage from the LP solution for selected shovel regions. An allocation is made when it is found that a particular shovel has enough capacity to remain as longer as possible (during the period) at a given face, hence avoiding shovel movements and idling. Once all the shovel faces in ore have been allocated the routine moves to waste mining faces and allocates the remaining capacity to stripping the necessary waste. The engineer can intervene if the computer generated allocation is not practical. The model does not include a truck dispatching system as this falls outside the scope of this work. However, the model calculates the required truck capacity to achieve the scheduled production.

Control of mining at the footwall contacts is important for stratiform orebodies, since this is a major source of dilution from the footwall rocks. Pits to mine stratiform orebodies are generally designed so that mining from certain benches follows the assay or natural footwall. Usually it is not possible to selectively blast the ore portions of these mining faces, due to the dipping nature of the orebodies so that blasts from these usually include a considerable amount of waste depending on how the benches have been designed. The problem is really to determine the amount of dilution so as to be able to decide whether this material should be treated as ore, or waste or transported to the stockpile for possible future processing. In this model the computer calculates the dilution based on the geometry of the mining front. The mining front in such areas is traversed by a ore-waste contact line. This line is marked on the sections and the coordinates of selected points are used as input for estimating the dilution. The resulting dilution factors are compared to values defined by management as to what constitutes ore, stockpile material or waste and a decision is made accordingly.

TESTING AND MODEL VALIDATION

The model is being tested with data from the Nchanga Open Pit in Chingola on the Zambian Copperbelt where the orebody dipping at an average of 25 degrees is stratiform in nature comprising copper and copper-cobalt mineralization. The current size of the pit is 4.0 km *1.5 km (wide) * 405 m (deep) with a bench height 15 m. Management at the pit considers factors related to production capacity, mill feed grade, existing and budgeted mining, milling and smelting capacities, operating slopes, equipment maneuverbility and availability as well corporate goals such as cash flow and obligations to the customer when planning production for the pit. All these factors seem to be well represented in the STOPPS model. Operations are carried out on a 24- hour per day , 7 days per week basis. Production targets are set at 6 million tonnes of ore and 30 million BCM of overburden per year. The required monthly production is 510 000 tonnes and the cut off grade is currently 1.0 % total copper (TCu). For efficient operation the mill should be fed with R-O-M ore containing 2.03 % TCu. This head grade is achieved by blending ore from various sources(ex-pit and stock piles). Although long range pit designs and grade estimation have been computerized, short term production scheduling is mostly manual with limited application of spreadsheets and data bases. The complexity of the vast Nchanga Open Pit operations precludes direct application of commercial mining software for short term scheduling. Thus, the STOPPS model comes in handy as a tool for short term scheduling at the pit.

Three quality parameters were considered in the schedule, namely total copper, acid soluble copper, and cobalt grades as is the practice at the mine. The programm was run using all the data required to manually generate a monthly production schedule. The reserve base by cut by bench is normally generated using Datamine software. To apply the STOPPS model blast polygons for active shovel regions were input as series of points from mine plans. It is a common practice at the pit to blend ex-pit ore with that from stock piles in order to meet grade and tonnage targets. It was thus necessary to input details of stock piles into the model as potential sources of ore. Due to the nature of the orebody there is little flexibility as to the choice of mining areas. Nevertheless, the schedule has to be optimal with regard to contained metal, deviation from the call mill feed grade and allocation of equipment. Figure 3 shows part of the typical output format from the STOPPS model generated during a test run of the program. The resulting schedule was compared to the manually generated plan for that month and the former was found to superior in many aspects. For example, in the STOPPS model the solution to the blending problem shows the average grade of the R-O-M ore to be within 4 % of the call grade compared with 11.5 % for the manual schedule.

Currently, the computer program is undergoing further development especially with regard to improving certain aspects of user interface and incorporating the concept of re-scheduling in the event of unanticipated catastrophe such as slope failure, equipment breakdown, etc.

CONCLUDING REMARKS

In this paper it has been demonstrated that there is still scope for development of simple but effective models to handle the problem of short term mine production scheduling in polymetalic open pit mines with stratiform orebodies. By combining linear programming with a simulation model, it has been possible to realistically model the scheduling problem which is characterized by multidimensionality. The optimization criteria in the model, namely the maximization of contained metal equivalent in the run of mine ore and the minimization of the sum of deviations of different quality parameters from their call values reflects the need for constant mill feed grade at several plants. The simulation part of the model effectively handles the numerous procedures and computations of short term production scheduling. Modelling the short term production scheduling problem separately allows one to consider several factors which may not be possible when the schedule is treated as subproblem of a large model embracing long and medium term planning. The STOPPS model gives acceptable and better results than manual or semi-manual methods. The handling of various short term production scheduling tasks for stratiform orebodies as presented in this model constitutes a significant contribution to the current state-of-the-art in computer assisted open pit mine planning.

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                 NOP Monthly Production Schedule - November 1991
                 -----------------------------------------------
                                                                           Page 1A
General Info:
------------
          # active ore sources  = 9
                    in ore      = 4     minable = 2
                    in waste    = 5
                    stock pile  = 2
          Ore target   = .510D+06    t/m
          Min. poss.   = .500D+06    t/m
          Max. poss.   = .520D+06    t/m
          ---------------------------------------------------------------
          Blending param.   Iupper boundIcall gradeIlower boundIW. factorI
          -----------------I-----------I----------I-----------I---------I
          Total Copper:     I  2.60 %   I  2.03 %  I  1.00 %   I  1.00  I
          Acid Sol. Copper: I  1.95 %   I  1.00 %  I  0.45 %   I  0.80  I
          Cobalt:           I  1.00 %   I  0.45 %  I  0.10 %   I  0.02  I
          ---------------------------------------------------------------

                                                                           Page 1B
Final Schedule:
--------------
Shovel reg. Pos.prod[tpm] Optim.prod[tpm] T.Cu[%] A.S.Cu[%] Cob.[%] Eq.met[kg/t]
--------------------------------------------------------------------------------
33E070M03    .318D+06      .180D+06       2.52     1.94     0.31     .4293D+02
34E080M05    .341D+06      .138D+06       2.33     1.60     0.26     .3771D+02
Stkpile22    .200D+06      .172D+06       1.88     1.00     0.00     .2592D+02
Stkpile23    .050D+06      .026D+06       1.10     0.59     0.00     .1521D+02
--------------------------------------------------------------------------------
Total:       .909D+06      .516D+06
Average:                                  1.96     1.28     0.28     .3044D+02
Deviation:                 .006D+06        .07      .28      .24
Max. cont'd metal    =   .17785D05 tonnes

                                                                           Page 1C
Initial shovel alloc.(ore):
--------------------------
          One unit of  Y51     to shovel region  33E070M03
          One unit of  Y32     to shovel region  34E080M05
          One unit of  Cat992  to shovel region  Stkpile22
          One unit of  Cat992  to shovel region  Stkpile23

          Earliest poss. shovel move on  day  0.0   of the month

Truck req'ment (ore):
-------------------
---------------------------------------------------------------------
Shovel       Dump        Distance(m)       Cy. time(min)     Trucks/day
---------------------------------------------------------------------
 Y32         E/mill        3480               23.4              5
 Y51         E/mill        3680               24.7              6
 CAt992      E/mill        4970               33.4              1
 CAT992      E/mill        1280                8.6              1
---------------------------------------------------------------------

                                                                           Page 1D
Summary statistics:
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Stock pile delivery   =    6000.00       tonnes
Scheduled production  =    516000.00     tonnes
Waste mined in period =    2.50          million BCM
Current ratio         =    4.8 : 1
```

FIGURE 3. Part of the typical output format of the STOPPS model.

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APPENDIX 1: Formulation of the linear programming model in the STOPPS System.

(i) Objective function:

$$MaxZ=\sum_{l=1}^{mk} M_l*X_l-\sum_{k=1}^{qp} W_k*P_k-\sum_{k=1}^{qp} W_k*N_k$$

(ii) Deviational constraints for tonnage and grades:

$$\sum_{l=1}^{mk} X_l+N_l-P_l=Q$$

$$\sum_{l=1}^{mk}\sum_{k=1}^{pq} (G_{lk}-G_k)*X_l+N_k-P_k=0$$

(iii) Bounds on tonnage and grades:

$$\sum_{l=1}^{mk} X_l\leq Q_{max}$$

$$\sum_{l=1}^{mk} X_l\geq Q_{min}$$

$$\sum_{l=1}^{mk}\sum_{k=1}^{qp} (G_{lk}-G_{ku})*X_l\leq 0$$

$$\sum_{i=1}^{mk}\sum_{k=1}^{qp}(G_{ik}-G_{kl})*X_i\geq 0$$

$$X_i\leq T_i$$

(iv) Non-negativity:

$$X_i,P_k,N_k\geq 0$$

Where;

X_i	= Unknown tonnage of ore to be mined from shovel region i [t]
M_i	= Specific contained metal equivalent for shovel region i [Kg/t_{ore}]
P_k	= Positive deviation for quality parameter k
N_k	= Negative deviation for quality parameter k
W_k	= Weighting factor for quality parameter k
Q	= Total required ore production in the period [t]
N_t	= Negative deviation of ore tonnage from required production [t]
P_t	= Positive deviation of ore tonnage from required production [t]
G_{ik}	= Grade of quality parameter k from shovel region i
G_k	= Average grade required for quality parameter k
G_{ku}	= Upper bound for quality parameter k
G_{kl}	= Lower bound for quality parameter k
Q_{max}	= Maximum allowable production in the period [t]
Q_{min}	= Minimum allowable production in the period [t]
T_i	= Available tonnage of ore for mining from shovel region i in the period [t]
mk	= Number of ore shovel regions in the pit
qp	= Number of quality parameters in the R-O-M ore
i	= Index for shovel regions
k	= Index for quality parameters