*17th International Mining Congress and Exhibition of Turkey- IMCET2001, ©2001, ISBN 975-395-417-4*

# Draw Control Optimisation in the Context of Production Scheduling

M.L.Smith & D.Rahal
*Department of Mining, Metallurgical and Materials Engineering/JKMRC, The University of Queensland, Brisbane, Australia*

ABSTRACT: Draw control in caving operations involves a combination of scheduling and geomechanics. Geomechanical issues related to draw control have played the dominate role in past efforts to reduce stress, improve fragmentation and reduce dilution. Production scheduling algorithms have been more commonly applied in surface mining but can be used to integrate more traditional methods of draw control with production and development schedules for the life of a panel with the objective of maximising project value. The state-of-the-art in production schedule optimisation is reviewed and compared against the complications related to caving. A generalised outline of the draw control optimisation approach being pursued at the JKMRC is presented.

## 1 INTRODUCTION

Block and panel caving operations are conducted in massive, generally low grade, deposits, having both weak ore and waste which will readily fragment and flow once undercut (Figure 1). De Beers' Premier and Kofflefontein are illustrative of these methods

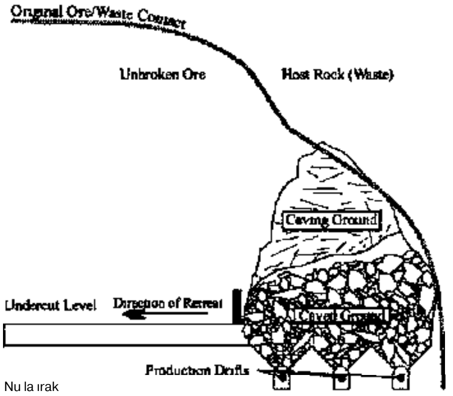

Figure 1 Panel cave extraction system.

At the Premier mine undercut levels are situated 15 m above their production levels. Caving normally starts once the undercut dimensions reach 100 x 100 m. Advanced undercutting is used at Premier, such that the extraction drawbells are developed after the undercut has passed over. The lag time between undercutting and completion of the extraction level can be no more than 6 months or there is the risk of ore compaction. The point loads developed when ore compaction occurs can damage the production level and necessitate rehabilitation of the mine workings before production can begin. In extreme cases, whole production drifts can be put out of service for a considerable length of time. The development pattern used at Premier is an offset herringbone. Parallel drifts are driven through the orebody and angled crosscuts connect the drifts at 15m intervals (the drawpoint separation distance has been increased to 18 m in some areas of the mine). The drawpoints on opposite sides of the tunnel are offset so that the drawpoints are all at different distances along the drift. The angled entry into the drawpoint crosscuts facilitates LHD entry. After cross cut development, a raise bore is driven upwards to the undercut level to provide a free face for blasting of the draw trough.

There needs to be tight coordination between development of the undercut and the maturation and activation of drawpoint production. If production lags behind development, stress will build on the production level instead of transferring to the boundaries of the panel. This will result in compaction of the ore, increased incidence of hangups in drawpoints and, in extreme cases, loss of tunnels and drawpoints in the production level.

At Koffiefontein Mine, the Front Caving method is used. This is a combination of block caving and sublevel caving that extracts ore on two production

Levels using a series of semi permanent drawpoints (SPD). A cross section of this layout can be seen in Figure *2.* This method offers two cost related advantages when compared to traditional caving. The first is the low cost of drawpoint support when mining in retreat, consequently the SPDs do not have to last the life of the mine. Undercutting costs are deferred by undercutting simultaneously the two production levels. Production is split between the two levels with an uneven production split between levels 48 and 49 (40 and 60 % of production respectively). Ore draw is also limited, initially, to a maximum daily draw down of 400 mm/day.

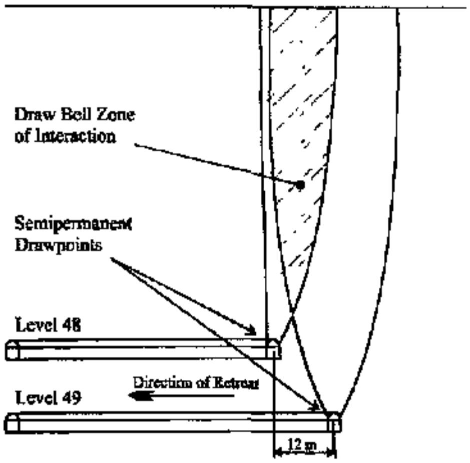

Figure 2. Front cave extraction system.

In sublevel caving, the orebody is blasted whilst the surrounding waste rock collapses during draw. Operations in the orebody are undertaken in roadways developed at relatively small vertical intervals. Scheduling of development in advance of production becomes extremely complex with place-changing of jumbos, LHDs and production drills occurring on the roadways, sublevels and production level. Ore is fragmented using blast holes drilled upwards in fans from these headings, allowing the waste rock to cave, then ore is extracted by front end loaders from the production drifts (Figure 3). As broken ore is extracted at the drawpoint, fragmented ore and enclosing caved waste *displace* to fill *the* void. Brady and Brown (1993) note that the mining method is characterised by relatively high dilution and low ore recovery, which has limited its application. Nevertheless, there is currently a resurgence of interest in sublevel caving as an underground mass mining method in Australia due partially to the increasing cost of supported methods of mining, particularly those requiring backfill.

All these methods of caving share some key characteristics:

- Close sequencing *of* development, undercutting and production
- Steady production to maintain fragmentation and flow and reduce stress
- Mobility and mixing of ore as a function of production
- Frequent and largely unpredictable loss of drawpoints
- Production sourced from a single block for a substantial portion of the mine's life
- An emphasis on minimising dilution throughout a panel's life

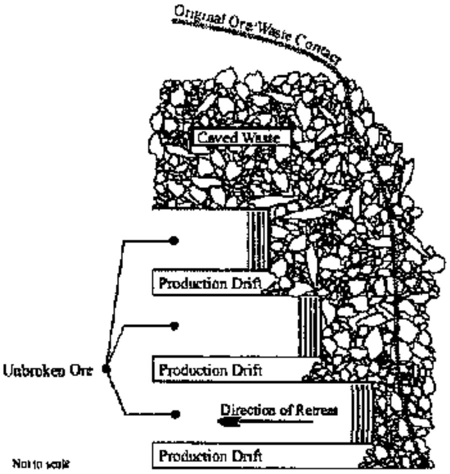

Figure 3. Sublevel cave extraction system.

In the larger context of life-of-mine profitability, draw control must be viewed as the central strategy mat integrates all of these characteristics of caving methods. Draw control encompasses sequencing and scheduling of development, production and the materials handling system with the dual objectives of minimising mining costs and dilution. Thus, draw control cannot be limited to the individual drawpoint but must account for the scheduling of drawpoint production over the life of the panel. Failure to closely follow undercut progression with activation of the underlying drawpoints will result in compaction of the fragmented ore, poor fragmentation and propagation of the cave and transferral of stress to the production level.

Mixing of the fragmented ore occurs both vertically and horizontally. Vertical mixing is a function of the fragment size distribution and results from fines rilling though coarser material. In the case of

Controlling blast fragmentation. In block caving, horizontal mixing results from uneven draw with ore migrating to columns of more mature (heavier drawn) draw points. As a result of mixing between columns, the reserve model is dynamic rather than static as is the case when scheduling is based on block models associated with surface mines or other smaller-scale stoping methods. Therefore, it is extremely difficult to solve the block cave scheduling problem simultaneously for multiple production periods since the contents of the columns in the reserve model are a function of production. The effectiveness of time-dynamic optimisation becomes even more questionable when the availability of the drawpoints and production tunnels is considered as these are frequently out of action due to hangups and failure.

The need for a rational approach to draw control is particularly important in terms of the longevity of a panel. One panel is likely to be the main source of production for many years. Poor draw control early in the panel's life can result in compounding difficulties in draw, dilution, low utilisation and ground control over time. A systematic approach to regulating draw over the life of the panel is essential, especially if that approach is based on an optimisation methodology which is capable of estimating the impact of poor draw practice on key issues such as dilution and equipment utilisation.

## 2 TRENDS IN PRODUCTION SCHEDULE OPTIMISATION

Research into pit optimisation and scheduling has evolved into a reliance on LP-based heuristics, following on the early work in pit optimisation using graph theory for ultimate pit optimisation [Lerchs, 1965] and LP decomposition for long-term scheduling [Johnson, 1968]. Since the 60s, these methods have dominated the mining industry. While the original simplex-based algorithms have been greatly enhanced in terms of speed and flexibility, both the underlying assumption of deterministic data and a top-down hierarchical approach to optimisation have been retained. In contrast, scheduling applications in petroleum manufacturing, transportation and chemical industries have concentrated on scheduling using Mixed Integer Programming (MIP). Prior to recent computational and algorithmic advances, large-scale open cast mine scheduling problems were correctly perceived as being intractable when formulated as an MIP. In light of tremendous recent advances in MIP algorithms, computing power and parallel solvers, this is no longer the case. Recent advances in MIP-based scheduling applications are particularly relevant to underground scheduling applications such as draw control. The order relationships between sequencing of development and production and the order in which drawpoints are brought into production necessitates the use of binary (0/1) variables. This negates the option to apply traditional LP formulations, requiring the more computationally intensive use of MIP with Branch and Bound (B&B) searches.

Outside the mining industry, MIP-based production scheduling is the norm, especially in manufacturing [Pan, 1997], the chemical industry [Pinto, 1995] and petroleum [Lee. 1996]. Of particular importance are the methods these industries use to solve large-scale MIPs. MIP problems are difficult to solve [Papadimitriou, 1988], but a number of specialised algorithms based on Branch and Bound search, LP relaxation and cutting planes have been developed to efficiently solve these problems [Nemhauser, 1988]: the staircase structure of the scheduling MIP formulation must be exploited by a variety of means such as Special Ordered Sets (SOS), priority ordering, initial starting solutions, decomposition and preprocessing to aggregate constraints and fix variables. Extremely promising results have been realised using these techniques. Hane [1995], solved airline fleet assignment problems with over 22000 binaries via aggregation, benders decomposition and the Interior Point algorithm used for LP relaxation. Smith [2000] used block precedence relationships in open pit production scheduling to assign priority orders and fix integer variables, as well as a number of other B&B search strategies to solve ore blending problems with over 800 binaries within a cpu second on a 400mHz Pentium II.

MIP in production scheduling has only recently begun to be accepted in mining. Underground production scheduling applications include the scheduling of block cave draw points [Chanda, 1990] and slopes [Trout, 1995]. In surface mining, there have been only a few applications of MIP-based production scheduling [Caccetta , 1998; Graham-Taylor, 1992; Barbara, 1986]. Smith [1998] applied GP and MIP to the short-term production scheduling problem in large surface mines [Smith, 1999] and for blending and inventory control in phosphate mining.

Only in recent years have significant applications been used in underground mining. Trout [1995] used MIP to schedule ore production and stope backfilling at Mount Isa Mine. Chandra [1990] used MIP to schedule drawpoint production in a block caving operation. Muge and Pereira [1979], followed by Ribeiro [1982] applied dynamic programming to short-term production scheduling in sublevel stoping. Davis and Morrison *[1999]* discussed the use of Datamine's floating stope heuristic and its use in evaluating alternate stope configurations under conditions of geologic uncertainty, with the algorithm itself described by Alford [1995]. Another stope configuration heuristic, using the

Maximum Value Concept, was reported by Ataeepour and Baafi [1999] Orvanic and Young [1999] used MIP and Special Ordered Sets of type 2 (SOS2) to optimise stope geometry by finding the consecutive sequence of blocks in a panel that yielded the maximum value.

All of these studies have concentrated on determining the optimum configuration of ore blocks for a stope. None address the issue of production scheduling. The only reported application to sublevel cave production schedule optimisation was a MIP model developed for the Kınına mine by Almgren [1994]. In the Kiruna model, Almgren attempted to find an optimal schedule for the life of the entire mine, solving simultaneously for all periods. He encountered two difficulties: the resulting MIP was so large that an optimal solution could not be ensured, and uncertainty in the production system, geology and mixing rendered an optimal solution highly suspect. He concluded that single production period scheduling using a long-term objective function as suggested by Gershon [1982] was an acceptable alternative. Smith [2000] has demonstrated that a sequential MIP optimisation approach to substantial short-term production schedules is feasible even with modest computational resources.

Guest, et al. [2000] describe De Beers' MIP for block cave production scheduling currently in use in Koffiefontein. The De Beers scheduling system contains the primary components necessary for a block or panel scheduling system. The draw control system in use at Koffiefontein can be seen in Figure 4. De Beer's mineral resource auditing system (MINRAS) contains data on the panel contents, draw column and drawpoint status, and the availability of support facilities. This information is passed to the draw control scheduling program to determine the optimum draw schedule. The constraints currently used in the Koffiefontein MIP focus on block contents, block sequencing, and the availability of granbies. Once the draw schedule has been defined and implemented, the Koffiefontein vehicle monitoring system, Prodman dispatch, sends production details to the MINRAS system for use in updating the panel contents. Draw schedule optimisation then continues on a period by period basis.

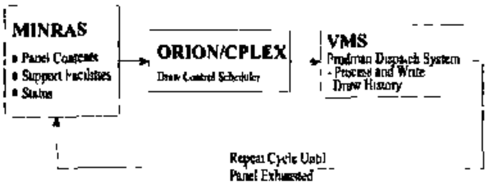

Figure 4 Data flow in the Koffiefontein draw control system

A more comprehensive De Beers scheduling system is being developed which includes a mixing module. The mixing module does not sit within the MILP, but is updated via the mine vehicle monitoring system. The production data is used to calculate the degree of mixing that has taken place as a result of the day's loading. This data is fed directly into the MINRAS database for use in determining the current panel contents for the next planning period. The MILP to determine the optimum draw schedule for each period with an objective based on maintaining a smooth, inclined dilution front. Guest, et al. [2000] report the usage of the mixing module and a time dynamic formulation based on NPV maximization.

## 3 GEOLOGIC UNCERTAINTY

Two sources of resource uncertainty limit the effectiveness of any scheduling system applied to caving. Mixing of the ore during draw has already been described and can only imperfectly be accounted for using empirical mixing models. This problem will be less severe in sublevel caving operations where there is limited height of draw and where control of blast fragmentation can be used to limit rilling. The other source of uncertainty arises from the spatial variability of the ore's characteristics - geologic uncertainty.

Geologic uncertainty's detrimental effect on mine planning and scheduling has been noted in recent articles which use simulated deposit models as input to the scheduling process. Ravenscroft [1992] describes the impact on production scheduling of deposit uncertainty using Conditional Simulation (CS). Dimitrakopoulos [1998] demonstrates that CS reproduces the underlying variability and spatial distribution of deposits and their use in open pit optimisation. Recent papers have used CS as a means of geologic risk assessment m: ultimate pit optimisation [Thwaites, 1998], long-term scheduling [Rossi, 1997], short-term scheduling and grade control [Blackwell, 1999; Dimitrakopoulos, 1999], NPV maximisation of stopes [Davis, 1999] and reduction of sulfur content in coal production [Costa, 1999]. While these studies have provided examples of the influence of geologic uncertainty as reproduced using CS, none have gone beyond basic sensitivity analysis. Smith and Dimitrakopoulos [1999] suggested a heuristic framework for quantifying uncertainty in short-term scheduling by coupling CS with Mixed Integer and Goal Programming (MIP, GP). The use of Stochastic Programming as a means of optimising production schedules in order to account for geologic uncertainty is discussed in Smith [2001].

Admittedly, at the current level of production scheduling as applied to block caving mere is little direct use for CS-based evaluations of geologic uncertainty: block caving operations are generally based on mining tons rather than grade or carats, an inevitable result of using an entirely non-selective mining method. Similarly, the technical level of mixing models do not account for the spatial distribution of planes of weakness and geologic boundaries, but for advances to be made in predicting caving, mixing and dilution, this technology will have to be supported with improved geologic models capable of accounting for uncertainty.

## 4 LIFE OF PANEL SCHEDULING

Production scheduling for open pit operations involves optimising the geometry and sequence of pushbacks and the production schedule for ore and waste over the entire life of the mine. This remains a largely trial-and-error methodology in which maximising NPV is balanced against a production schedule and an operationally feasible mine plan Time-dynamic scheduling over a rolling horizon can resolve the limitations of production scheduling, as all production periods are optimised simultaneously. In the rolling horizon approach, more emphasis is placed on finding the optimal solution for the most immediate series of production periods since these are deemed to be most critical and associated with greater certainty in terms of the state of the production system and stability of the market. More distant time periods represent longer phases of production and simplifying assumptions. In the caving application, these simplifying assumptions would include the availability of drawpoints and a static resource model. While this is the norm in manufacturing production schedules [Sethi, 1991] the few time-dynamic MIP applications in mining [Smith and Tao, 1993] have been limited to relatively small problems. Current practice aims at simultaneously optimising across all production periods for the mine's life with the aim of maximising project value. Both Guest [2000] and Almgren [1994] describe a time-dynamic formulation, but in practice both adopted *a* sequential optimisation approach. In reality, this approach increases problem size without adding to the quality of the solution; changes in technology, revised reserve estimates and shocks to the market inevitably negate any production plan extending beyond a relatively short time frame. Outside of the mining industry, production scheduling is optimised using a rolling front which consists of the minimum number of periods deemed necessary for making decisions relating to production and inventory planning; any changes in production capacity or demand are accounted for by «optimising starting from the current period. For block caving this is a methodology mandated by the dynamic nature of the resource model. In the context of surface mine production scheduling, long-range targets for production are still necessary in order to maintain a rational sequence of pushbacks that balance ore and waste removal [Tan, 1992]. In contrast, for the caving application, the production targets are based on minimising the deviation of the ore/waste horizon from the ideal surface. Thus, a minimum curvature surface becomes the long-range goal retained in each period.

## 5 DRAW CONTROL

Under ideal conditions of good fragmentation and draw without hangups, drawpoint scheduling would be a relatively straight forward process, especially if we could assume that the flow of ore is not spatially dependent on in-situ rock mass characteristics such as mineralisation and the ore/waste boundary. Unfortunately, draw rates and availability are not predictable over the life of a panel. Drawpoints in the active mining front are frequently closed or continued at reduced capacity due to unforeseen events such as early closure of drawpoints due to dilution and failures in the supporting materials handling system. Thus, scheduling is complicated by over producing in some drawpoints, bringing drawpoints on line at too early a date and by reassignment of production equipment. The long-term effect of deviations from an ideal schedule is that dilution levels become much more locally variable. As a result, a higher percentage of ore is left in the panel than would be the case if a smooth production front had been maintained. Therefore, the objective of draw control scheduling is to develop the means of minimising the impact of deviations from an ideal schedule in order to maximise ore recovery by minimising dilution and providing a stable mill feed.

For a given deposit realisation consisting of spatially variable mineralisation and structures, there is an optimal sequence of development and production that will allow the maximum extraction of ore from a panel. Heslop and Laubscher (1981) discussed some of the basic principals of block caving production, including: (1) lower the ore/waste interface as evenly as possible, (2) work all drawpoints simultaneously to achieve maximum interaction between drawpoints, (3) regulate drawpoint production as a function of the contained ore to avoid lateral migration of waste into isolated ore, and (4) maintain the ore/waste interface at a constant inclination so that the lines of drawpoints are depleted simultaneously as new lines come into production. The ore/waste boundary can be treated as a dilution front. In order to maximise the extraction of ore, this dilution front should be subparallel to the hangingwall and the plane of extraction of the system of retreating roadways, each of which terminates in a drawpoint. Excessive extraction from one or more drawpoints will result in increased curvature of the waste contact allowing a greater surface of dilution. As the curvature of the dilution front increases, so does the potential for early loss of ore. Poor control of the extraction sequence will become increasingly difficult to compensate for as the panel matures resulting in loss of reserves. Thus, scheduling of draw, retreat and development must always work towards the life-of-panel objective - maintaining a dilution front of minimum curvature.

## 6 FORMULATION

Draw control optimisation for a caving operation is a non-linear problem that cannot be solved simultaneously for all production periods. This characteristic arises from ore mixing changing the draw column contents throughout the life of the panel. The extent of this mixing is m turn affected by mine production practice. The dependence of ore recovery on mining practice requires that the draw control problem be solved on a period-by-period basis. The long-term draw plan is implemented through the development a long-term objective which is based on the ideal draw strategy for the remaining life of the panel and the draw history of the panel. Figure 5 shows a snapshot of a block cave draw scheduling system as implemented after n production periods. Draw scheduling for the current period begins by transferring draw history data into a series of preprocessing modules. These modules determine the current contents of the individual draw columns based on an ore mixing model and the draw history of the columns. Additional information on the resources and support facilities available during the period (e.g. drawpoint availability, LHD availability, ore pass status, production targets) is also handled in preprocessing. This data is formatted as a parameter file for use in the optimisation module.

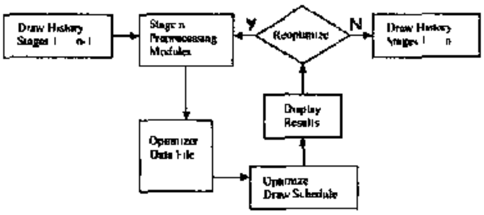

Figure 5. Procedural flow for sequential draw control scheduling.

The optimisation module then develops a draw plan based on the history of draw and the availability and maturity of drawpoints and the materials handling system. If limits on production prohibit the development of a feasible draw plan constraints on production must be relaxed and the problem resolved. Typically, this would involve increasing resource levels in the material's handling system, advancing the development schedule, or, at worst, relaxing production targets for mat period. The period-by-period planning process continues until a satisfactory draw schedule is produced. The resource model is then updated as mining proceeds and the entire cycle is repeated in subsequent planning periods.

The objective function seeks to minimise the deviation of column heights from the ideal surface (Figure 6). To achieve minimum curvature, production would come from the drawpoints lagging behind the ideal draw plan (designated by Xs) while all others would be closed during that scheduling period.

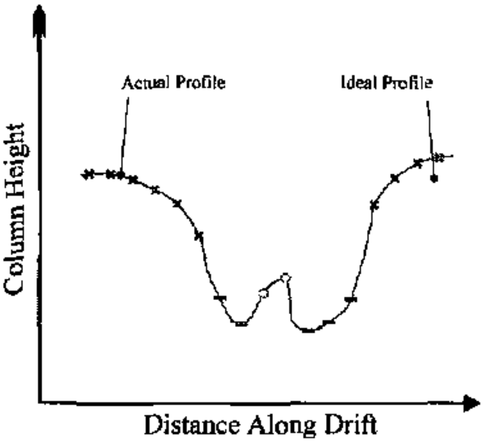

Figure 6 Ideal versus actual draw profiles

Now suppose that two of die allocated drawpoints have become unavailable due to ore hangup early in the production period. The LHD servicing the drift would not be able to achieve its draw. As a result, the LHD must draw from the suboptimal drawpoints to achieve its production target. The two best candidates are the two drawpoints marked by circles in Figure 6. These drawpoints break the continuity of the ore/waste contact by lagging behind their neighbours. Reallocating draw from the two hungup drawpoints to these two drawpoints will meet the LHD's production target while moving towards the ideal draw profile.

Order relationships have to be maintained to control die pattern m which drawpoint production is initiated. For example, at De Beers' Premier mine the pattern of initiating drawpoints is based on a fixed angle chevron pattern and a drawdown angle of 27 degrees (Figure 7). The orientation and angle of this pattern is controlled by precedence constraints between drawpoints in the same column (perpendicular to the direction of retreat).

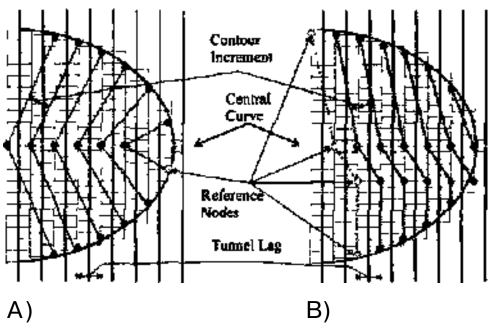

Figure 7. Ideal draw profiles as a) chevrons or b) variable configurations.

Any solution to tie drawpoint scheduling problem should ensure high utilisation of the materials handling system. As the result of non-ideal draw practice and the loss of drawpoints, solutions in the latter stages of a panel's life can identify that production should occur in fewer drawpoints or production tunnels than would be operationally acceptable, resulting in poor utilisation of tunnels and LHDs. In addition to minimising dilution, the solution should maximise equipment utilisation, even if this goal *is* secondary to resource recovery. Alternative methods are being explored which may accomplish this including: (1) a more elaborate constraint program as a front end to the M1LP, (2) including equipment utilisation constraints or (3) using hierarchical goal programming optimising on resource recovery first and equipment utilisation second.

## 7 CONCLUSIONS

There are clear advantages of using production scheduling as a major component of draw control in caving operations including: (1) minimising dilution and maximising resource recovery, (2) maintaining good cave propagation and fragmentation, (3) maintaining high equipment utilisation while avoiding bottlenecks in the materials handling system and (4) integration of the entire development and production system. De Beers and Kiruna are clearly moving in this direction by adopting MIP-based scheduling. With the rising interest in applying caving systems to increasingly more challenging settings, the mining industry is investing in developing a generalised approach to draw control which is built around scheduling.

There have been significant recent advances in production schedule optimisation both in the general industry and in mining. None of the scheduling methodologies currently available fully address complications associated with caving, in particular ore mixing and frequent loss of drawpoints. Both of these negate the use of time-dynamic solutions to the scheduling problem and require that production scheduling be carried out as an iterative sequence of single production period solutions. In each period, the history of draw is used to update the contents of a resource model while the current availability of the materials handling system and drawpoints constrains the solution to account for operational limitations and high system utilisation.

The clear objective of draw control is to minimise dilution over the life of the panel. Production scheduling aims at achieving low dilution by minimising the curvature of the ore/waste interface away from the ideal surface. In each period, the history of draw is used to determine the difference between the height of columns in the resource model and the ideal level. The objective function then minimises the deviations in column heights as much as possible given the availability of drawpoints, production capacity maturity rules and limitations imposed by the state of the materials handling system.

The scheduling system envisaged herein requires a significant body of research in a number of issues related to draw control and modelling. Accurately predicting the mobility of ore during caving and draw is essential using an objective function based on modelling the position of the ore/waste interface. Otherwise, an "optimal" solution will be rendered useless due to the inaccuracy of the underlying resource model. Likewise, the collection of data on the production of each drawpoint has to be rigorously maintained and integrated into the production scheduling system. There are significant computational difficulties as well associated with formulating math programming models that include order constraints and scheduling of production equipment and development as large MIPs. This is a very difficult class of problem to solve requiring expensive solution engines and very powerful computers. In order to bring this technology to the mine site at the level of the production engineer will require research on efficient formulations and speed enhancing algorithms. While the application of MIP draw control is not a trivial problem, the technology needed to produce an effective first generation system is already on the shelf and the mining industry need only recognise the nature of the challenge and set about finding the solution.

## ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of the Director - Operations, Corporate Headquarters, De Beers Consolidated Mines and the Consulting Geotechnical Engineer Mining

In particular the contributions of Gert van Horn, Pat Bartlett, Kim Nesbitt, and Linda Hannweg of De Beers operations who assisted in the understanding and initial development of this work

## REFERENCES

Alford, C Optimisation m Underground Mine Design *25th Application of Computers and Operations Research in the Mineral Industry Proceedings,* Brisbane, Australia, July 1995 AusIMM, 213-218

Almgren, Torgny 1994 *An Approach to Long Range Production and Development Planning with Application to the KirunaMme Sweden* PhD Thesis, Lulea University of Technology

Ataee-Pour and Baafi, 1999 *Slope Optimisation Using the Maximum Value Neighborhood (MVN) Concept 28th Symposium on the Applications of Computers and Mathematics in the Minerals Industry,* CSSM, Golden, Colorado, October 1999 493-502

Barbara , R W and R V Ramani , *Generalized muitipenod MIP model for production scheduling and processing facilities selection and location* Mining Engineer, 1986( February) p 107-114

Brady and Brown, *Rock Mechanics for Underground Mining,* $2^{Bd}$Ed Chapman and Hall, 1993

Blackwell, G , M Anderson, and K Ronson *Simulated grades and open pit planning - resolving opposed positions* In *27thAPCOM* 1999 CSM,Golden,CO SME

Caccetta, L, P Kelsey , and L Giannim *Open Pit Mine Production Scheduling* in *3rd Regional APCOM Symposium* 1998 Kalgoorlıe

Clianda, E C K *An application of integer programming and simulation to production planning for a stratiform ore body* Mining Sei and Tech, 1990 II p 165-172

Costa, J F , Koppe, J C , Dimitrakopoulos, R, and Ztnghano, A , *Incorporating uncertainty associated with prediction of geological attributes in coal mine planning* in *26th APCOM* 1998 London, 451-459

Davis, B M and J Mornsion *Enhanced underground design through optimization and risk assessment* In *27th APCOM* 1999 CSM, Golden, CO SME

Dimitrakopoulos, R *Conditional simulations and objective economic functions for grade control Implementations alternatives, pros & cons* SME Meeting, Denver, Co, March 1-3, 1999

Dimitrakopoulos , R *Conditional simulation algorithms for modelling orebod\ uncertainty in open pit optimisation* International Journal of Surface Mining, Reclamation and Environment 12,1998 p 173-179

Graham-Taylor, T *Production scheduling using linear and integer programming* in *AusIMM Annual Conf, State of the art - a product of 100 \ears of learning* 1992 Broken Hill, NSW AusIMM

Gershon, Mark *Heuristic Approaches for Mine Planning and Production Scheduling* Int J of Mining and Geo I Eng Vol 5(1),1-13 1997

Guest, A R , Van Hout, G J, Von Johannides, A, Scheepers, *LF An application of linear programming for block cave draw conti ol,* MassMın 2000, Brisbane

Hane, C A , et al *The fleet assignment problem solving a large-sca'e integer pi ogi am* Math Prog, 1995 70 p 211-232

Heslop, T Glen and Laubscher Dennis H 1981 Draw Control in Caving Operations on Southern African Chrysotile Asbestos Mines *Design and Operation of Caving and Sublevel Stoping Mines* Stewart, Daniel R (editor) SME, New York, 755-774

Johnson, T B *Optimum Open Pit Mme Production Scheduling, m Mining Engineering* 1968, University of California Berkeley p 120

Lane, K.F *The economic definition of ore cut-off grades in theory and practice* 1988, London Mining Journal Books I49pp

Lee, H , Pinto, J M , Grossman, I E, Park, S *Mixed-Integer Linear Programming model for refinery short-term scheduling of crude oil unloading with inventory management,* lnd Chem Res,35,1639-1641,19%

Lerchs, H and I F Grossmann, *Optimum Design of Open-Pit Mines* Transactions, C I M , 1965 LXVII1 p 17-24

Muge, Fernando and Pereira, Henrique Garcia. 1979 Short-term Planning in Sublevel Stoping Methods *16th Application of Computers and Operations Research in the Mineral Industry Proceedings,* Tucson, Arizona, October 1979 SME, 323-334

Nemhauser, G L and Wolsey, L A , *Integer and Combinatorial Optimization,* W dey Interscience, 1988

Ovanic, J and Young, D S 1999 Economic Optimization of Open Stope Geometry *28th Symposium on the Applications of Computers and Matkematics* in *the Minerals Industry,* Colorado School of Mines, Golden, Colorado, October 1999 Colorado School of Mines 855-862

Pan, C H *A study of integer programming formulations for scheduling problems* Int J Sys Sei, 1997 28(1) p 33-41

Papadimitnou, C H and K Steıglıtz *Combinatorial Optimization algorithms and complexity* seconded 1988 Dover 496 pages

Pinto, J M and IE Grossmann *A continuous time mixed integer linear programming model for short term scheduling of multistage batch plants* lnd Eng Chem Res, 1995 34 p 3037-3051

Ravenscroft , P J *Risk analysts for mine scheduling by conditional simulation* Trans Instn Min Metall (Sect A Min industry), 1992 1Ol(May-August) p A104-A108

Rlbeiro, Luis Tavares 1982. *Dynamic Programming Applied to the Mining Sequence Optimization in a Sublevel Stoping Exploitation* 17th Application of Computers and Opera tions Research in the Mineral Industry Proceedings, CSM, SME, 494-499, 1982

Rossi, M E and B H Van Brunt *Optimizing Conditionally Simulated Orebodies with Whittle 4-D* In *Optimizing with Whittle Conference* Pp 119-128 1997 Perth

Sethi, S and G Sorger *A theory of rolling horizon decision making* Annals of Oper Res, 1991 29 p 387-416

Smith, M L and W Y Tao *Mine production scheduling for optimization of plant recover]' in surface phosphate operations* Int J Surface Mining, 1994 9 p 41-46

Smith, M L *Optimizing inventory stockpiles and mine pro duction an application of separable and goal programming to phosphate mining using AMPL/Cplex* Int J Surface Mining, 1998 p 61-64

Smith, M L and R Dimitrakopoulos *The influence of deposit uncertainty on mine production scheduling* Int J Surface Mining, 1999

Smith, M L *MIP solution strategies for short-term production schedules* Trans Inst M in Metall Section A mining ind, 2000 (submitted)

Smith, M L *Integrating conditional simulation and stochastu programming an application in production scheduling* APCOM 2001, Beijing, PRC, April, 2001

Smith , M L *Optimizing short-term production schedules in surface mining Integrating mine modeling software with AMPL/CPLEX.* International Journal of Surface Mining, Reclamation and Environment 12, 1998 p 149-155

Tan , S and R V Ramani *Optimization Models for Scheduling Ore and Waste Production in Open Pit Mines* In *23rd APCOM* 1992

Thwaites, AM *Assessment of geological un<.ertamt\ for a mining project ıtı27thAPCOM* 1998 London IMM

Trout, L P Underground Mine Production Scheduling Using Mixed Integer Programming In APCO