Company Strategy - A Basis for Production Scheduling of an Open Pit Complex

Dr Rossen Halatchev

Qualifications: M Sc in Surface and Marine Mining, Moscow Mining Institute, Russia.
Ph D, University of Mining and Geology, Bulgaria.

Experience: Medet Copper Open Pit Mine, Bulgaria.
Department of Surface Mining, University of Mining and Geology, Bulgaria.
Mining Division, Ministry of Industry, Bulgaria.

Currently: Senior Research Fellow, W H Bryan Mining Geology Research Centre, University of Queensland, Australia.

Abstract

The successful management of every mining company in the conditions of the market economy is predetermined by its strategy, which always synthesizes some level of a practical experience and scientific knowledge. The strategy as a prediction envisages the fulfillment of the long-term objectives of the company and, in this way, it forms the compulsory framework of the planning of the mining operations.

The article gives an elaborate analysis of the mutual connection between the strategy and the production scheduling of a mining company in terms of long- and short-term planning. An original optimization solution of the problem of the production scheduling is suggested on the basis of the strategic supply-demand function of the final product for the case when the company simultaneously runs a complex of a few independent open pit units. The solution suggested is applicable for deposits of polymetallic ores containing an unlimited number of economic metals. A case study is provided and relevant conclusions are drawn on the possibilities of the suggested optimization solution for reaching the adequate management of the mining production in constantly varying market conditions as well as for a significant increase of the company profit.

Introduction

The prosperous development of each mining company in the contemporary conditions of the market economy is impossible without the development and application of a strategy of action in long-term plan. This concept is adopted widely in world wide mining practice and especially by the biggest companies, which, with their participation in the international market, influence to one or another degree the pricing of the final products from mining activity.

In the field of surface mining of ore deposits the formation of a mining strategy has its own specific features. Due to the fact that the exploitation of such deposits deals with the management of huge capital investments, in world mining practice the approach of staged exploitation has already been adopted. Its wide application assigned it the role of a synonym for an effective economic approach to open pit design and production scheduling.

One of the basic requirements for developing an effectively acting mining strategy is the presence of a rich arsenal of scientifically grounded methods for predicting the relevant processes and phenomenon. In this relation open pit design and production scheduling has an indisputable advantage over underground mine design and production scheduling [*Pareja et al., 1995*].

With the development of the analytical method of Lerchs-Grossmann in 1965 [*Lerchs et al., 1965*] for open pit design the fundamentals of a new era of the pit design were established. This method served as a powerful spur for the wide application of computerization for the replacement of complex calculating procedures, a good example of which is the software of Whittle Programming Ltd [*Whittle et al, 1991*]. In parallel with the development of analytical methods of open pit design, very good theoretical results have also been achieved regarding mine planning [*Wooller, 1992; Onur et al. 1993; Halatchev, 1993; Kim et al.,1994; Steffen, 1996; Dimitrakopoulos, 1997; Whittle, 1998*].

The present paper suggests an original solution to the problem for optimizing the production scheduling of an open pit complex, which is applicable for deposits of polymetallic ores. It includes an optimization of the pit complex production in regard to the types of economic metals recovered from the ore treatment. In this way a real connection is achieved between the supply-demand function, which operates with metals as final market products, and the predicted metal quantities from the optimization of the production scheduling.

Mining Strategy and Production Scheduling

The mining strategy as a definition can be accepted as a scientifically grounded prediction for the long-term behavior of the mining company aiming to reach definite objectives at the exploitation of an open pit complex. The development of a strategy is necessary as a means for forming the long-term macro-economy policy of the company in the conditions of a great degree of uncertainty regarding data on the factors influencing company management. The strategy includes the determination of the main objectives to be reached. The major objective of every company, undoubtedly, is the realization of a positive economic result from the mining activity. Generally it focuses on the maximization of the company profit although there are other alternatives. To this end the solution of the main problem of the mining strategy is the optimization of open pit design and production scheduling (OPDPS) for the whole life of mine (LOM). Nowadays, in the theory and practice of surface mining two basic approaches for solving this problem are known [*Halatchev et al., 1996*], namely:

First approach: planning of the annual ore production as a constant quantity that is a function of the available mill capacity of the processing plant; achievement of a stabilization of the mining rate for effective utilization of the basic mining equipment; minimization of the annual waste production.

Second approach: planning of the annual mining rate as a constant quantity; the annual ore production is a variable quantity, but the processing plant is fed with a constant ore quantity, which is achieved with the use of stockpiles; minimization of the annual waste production.

The widest application in the current practice of surface mining has the first approach. The second approach, however, has the advantage for reaching more intensive development of the mining operations within the pit space. This approach uses stockpiles as buffers between the mine and the processing plant as a means for supplying a constant averaged quantity of ore. There are not, however, any proofs in contemporary research to confirm its economic effectiveness in a practical situation is higher than the one of the first approach. Hence, the choice of a given approach depends on the objectives of the mining company.

In both approaches the determination of the annual ore quantity to be mined and processed is treated as a separate problem preceding the optimization of OPDPS. This problem was investigated by many scientists. The methodology of its solution initially took the direction of requiring the determination of the mine and mill capacity for the whole LOM as a function of the available ore reserves after their economic assessment. This is confirmed by the investigations of Matheron, Masse, Margolin [*Nikitin, 1988*]. The solution of this problem aimed to determine the optimum capacity of the mine and processing plant before the commencement of the exploitation of a new ore deposit. The mill capacity being once determined was used mostly as a measure of the annual ore production during normal mine development. Later the problem of determining the mine and mill capacity found place in Lane's theory regarding the optimization of the cut-off grade [*Wooller, 1997*]. During recent years, and especially after the globalization of the principles of the free market economy, the approach of determining the annual ore production took another direction. It treated the determination of the annual ore quantity and the final products in it respectively on the basis of the unique supply-demand relationship inherent in that kind of economy [*Gentry, 1988; McEachern, 1988. Noakes et al.,1993*]. This approach is very topical when metal prices have dropped dramatically in the world metal exchanges and have produced a crisis in the world mining industry.

Without launching out into explanations of the technique for evaluating the ore quantity for a given time period on the basis of the supply-demand relationship, which is known in the mining research practice and more for the financial analysts, is necessary to stress that it operates directly with the metal quantity but not with the ore quantity containing the metal. The supply-demand relationship, in the context of the evaluation of the market value of the mining production, also supposes the treatment of metal production as a dynamic quantity that is constantly changing as the market conditions change. Hence, a conclusion follows that the mining company should realize a long-term policy of working with a variable production of ore and metal respectively within the framework of the available mining and processing capacities.

The optimization of OPDPS for an open pit complex suggests bigger possibilities for maximizing the profit from mining activity in comparison with the one of a single open pit mine, especially when a big ore deposit is exploited. This can be explained with the possibilities of the application of the principle of waste deferment as a main principle of long-term planning, which leads to maximization of the profit through an optimization of the waste and ore production as well as of the number of the separate pit units of the open pit complex [*Halatchev, 1997*]. With this principle is established a dynamic link between the generation of pit shells in the Whittle method [*Whittle et al., 1991*] and the succeeding production scheduling, i.e. the pit design and production scheduling are treated only as two separate phases of the solution of the common problem for maximizing the profit from the operating activity.

Another problem of mining strategy, which has a direct effect on the optimization of the OPDPS, including the determination of the annual ore production, is the price prediction of the metals recovered from the ore. This problem, undoubtedly, is one of the most difficult to solve, especially with regards to the long-term forecasts. The reason can be explained with the existed level of the scientific knowledge development in this specific area. Generally the methodology of the metal price determination also uses the supply-demand function but probable-statistical methods are successfully being applied. The last ones use the model of the random quantity and random function [*Dowd, 1994; Halatchev, 1996*] which, however, don't reveal the cause-and-effect link of the process of price formation. They give some solution of the problem although with not a high degree of reliability. The reliability of short-term predictions is, undoubtedly, higher in comparison with the long-term predictions. It is recommended, for the benefit of the reliability increase of the long-term predictions, that we use predictions reflecting the average trend of the price variation while at the short-term predictions must take into account the price variation around the trend component of the long-term predictions.

The problem of the prediction of the different types of costs is similar to the problem of price prediction. However, although the price is a factor which the mining company cannot control (the tools for active intervention like hedging are of limited number [*Eager, 1997*]), the costs are entirely within the company control. That is why cost prediction ignores actual reserves without regarding the possibilities of existing mathematical methods but with regards to the application of new, more advanced technologies in the whole chain of the production process for increasing the economic effectiveness of the mining venture. This is the alternative that is being exploited at present in the current depressed economic time.

The prediction of metal prices and costs has a weak connection with the prediction of the inflation as a real economic process. Without taking into account inflation it is impossible to make a scientifically grounded economic analysis of the mining project. The prediction of inflation is necessary, first – for doing a project assessment with constant money units [*Gentry, 1988; Bilodeau, 1998*], which is a well known rule in the mining practice, and second – for determining the inflation component of the discount rate used in the discounted cash flow analysis of the project [*Smith, 1994*].

The prediction of the discount rate also represents a very important problem of the strategy as it reflects the company policy for recovering the capital invested in the mining project and a satisfaction of the investors' interest. This prediction treats not only the determination of the inflation and nominal components but also the risk component of the discount rate which takes into account the probable character of the influence of the geological, technological and economic factors.

In principle, there can be other objectives of the mining strategy, but they are generally applicable to lower levels of the company management as, for example, enabling a protection of the environment; rational use of the ore deposit in long-term aspect with a social emphasis; achievement of a safe working environment, etc. These objectives, undoubtedly, are of secondary importance for the company because their realization depend on the realization of the major objective that is an achievement of a positive economic result from the mining activity. Namely, this circumstance predetermines the exceptional importance of the problem for optimizing the OPDPS, which is a fundamental for achieving the major objective of the mining company.

Model of Production Scheduling

The model suggested for optimizing the production scheduling of an open pit complex is based on the Linear Programming (LP) technique that finds a wide application for mining related purposes. It means that linearity is accepted as an admission toward the mathematical description of the production scheduling. Indeed, there are proofs in the research practice arguing this admission for the benefit of the alternative [*Halatchev, 1995*].

The LP model exploits the idea for optimizing the production scheduling on the basis of a full discounted cash flow (DCF) analysis of the mining project. The DCF analysis as it is well known, has the advantage of being a dynamic integrated method allowing an adequate modeling of all real cash flows of the company. This analysis, of which the fundamentals were established in the 1980s [*Gentry, 1988*], gave enough proofs regarding its possibilities for improving the investment decisions in the mining practice.

Due to the fact that the application of the DCF analysis depends generally on the jurisdiction of the country where it has to be applied, the present model reflects only one possible variant of such a kind of analysis [*Halatchev et al., 1997*]. The aim of this author's approach is to demonstrate the principles of the model, which can easily be modified for different schemes of DCF analysis corresponding to different taxation systems and accounting standards.

The Objective Function of the LP model represents an expression of the Net Present Value (NPV) of the project as a criterion for assessing the economic effectiveness of the production scheduling. The NPV expression is worked out on the methodology for determining the Net Smelter Return (NSR) as another criterion of the economic evaluation [*Goldie et al., 1991; Noakes et al.,1993*]. This criterion, despite the fact that it has the disadvantage of being a static economic criterion, takes into account the whole range of costs inherent in the production process from mining to the marketing of the final products. The incorporation of its methodology means, first – an extension of the application sphere of the model through ignoring the fact whether the mining company sells a concentrate or a metal as a final product and, second – an achievement of an adequate modeling of the whole variety of real production costs. In this way the requirements of contemporary production scheduling are met in a way that includes many more parameters than the conventional open pit design.

The NPV criterion includes all parameters of the DCF flow analysis from the operating activities of the mining company as well as such taxation parameters as royalty and profit taxation. The capital investments are treated more generally and they are divided into three groups: for mining production, ecological and social purposes. The capital investments for mining production purposes are usually divided into three subgroups: capital expenditure, replacement capital and working capital. The criterion also incorporates a parameter of the financial activity of the company, the loan interest payment, with regards to the service of the loans borrowed only for mining production purposes. The rest of the parameters of the financial activity and the ones of the non-operating activities of the company are not included in the DCF analysis because they are related to activities, which don't deal with the direct exploitation of the ore deposit.

The present optimization model is applicable to deposits of polymetallic ores, which are being exploited widely in modern mining practice. It recognizes two ore types – basic ore and secondary ore. The Basic Ore type (BOT) is that ore which uses its own processing technology and meets the requirement of the processing plant for working with a given capacity of the available mills. The Secondary Ore Type (SOT) is that ore which uses another processing technology and there is not a practical limitation on its capacity in more general sense. Such a type of ore can be the marginal and sub-grade material of the gold deposits or the oxide ore of the copper deposits, which are processed by leaching. The Basic Ore type naturally plays a dominant role in the production scheduling of the open pit complex as a percentage of the production of the final products of the company. The metal, which has a dominant economic meaning regarding all metals produced from a given type of ore concentrate, is accepted as a 'leading metal' in the LP model. The model is developed under the assumption that only one type of concentrate is produced from each type of ore and an unlimited number of metals as final products can be produced from every type of concentrate.

The LP model optimizes the metal production for both types of ore; that is its distinguishing feature. Graphically it is illustrated in Figure 1, which reveals the relationship of the waste and BOT & SOT leading metal quantities in a cumulative form for the two limiting cases of leading the mining operation in an example open pit complex. This figure shows the feasible domain of the open pit complex, in which the Objective Function governs the optimization solution.

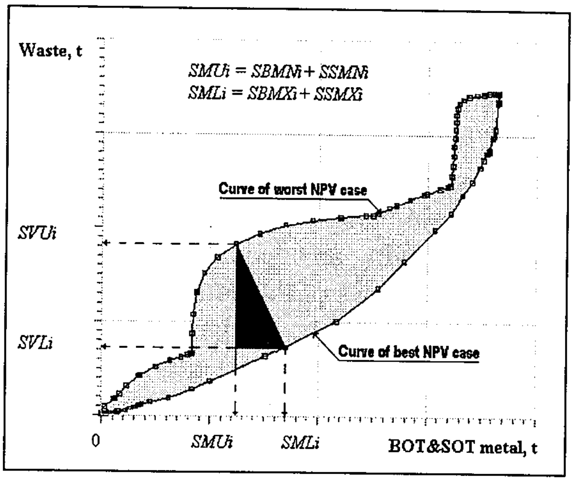

Figure 1: Common Cumulative Graph for an Open Pit Complex

As to the metal quantities of BOT and SOT, they are treated as variables in the model while the ore quantities are derived from them. The metal quantities are determined for every level of the whole production process by taking into account all possible technological losses including the deduction for a smelter treatment.

The model applies the first basic approach of OPDPS described above which puts an emphasis on working with a constant annual ore production and then stabilizing the mining rate.

The Objective Function of the model has the following expression:

$$
\begin{aligned}
\boldsymbol{NPV} = & \sum_{i=0}^{n} d_i(1-T)\left[(1-R_o-C^{mil})\left(\sum_{j=1}^{m_b} a_{b_{ij}} S_{b_{ij}}\right) - A_{b1_i} - \left(A_{b2_i} + \sum_{j=1}^{m_b} A_{b3_{ij}}\right)\right]\boldsymbol{M}_{b_i} + \\
& + \sum_{i=0}^{n} d_i(1-T)\left[(1-R_o-C^{mil})\left(\sum_{j=1}^{m_s} a_{s_{ij}} S_{s_{ij}}\right) - A_{s1_i} - \left(A_{s2_i} + \sum_{j=1}^{m_s} A_{s3_{ij}}\right)\right]\boldsymbol{M}_{s_i} - \\
& - \sum_{i=0}^{n} d_i(1-T)C_{w_i}V_i - \sum_{i=0}^{n} d_i(1-T)(TC_i + LIP_i + DA_i + EX_i + LCF_{i-1}) + \\
& + \sum d_i(DA_i - CI_i) - \sum_{k=1}^{m}\sum_{i=0}^{n} d_i h_{ki} \boldsymbol{NC}_{ki} - \sum_{k=1}^{m}\sum_{i=0}^{n} d_i u_{ki} \boldsymbol{DC}_{ki} \Longrightarrow \boldsymbol{MAX}
\end{aligned}
$$

where: $A_{b1_i}, A_{s1_i}, A_{b2i}, A_{s2_i}, A_{b3_{ij}}, A_{s3_{ij}}$ are coefficients.

Equation 1: $A_{b1_i} = (C^m_{b_i} + C^p_{b_i})(\gamma^c_{b_i}\gamma^m_{b_i})^{-1}$

Equation 2: $A_{s1_i} = (C^m_{s_i} + C^p_{s_i})(\gamma^c_{s_i}\gamma^m_{s_i})^{-1}$

Equation 3:

$$A_{b2_i} = (C^{sm}_{b_i} + C^{pe}_{b_i} + C^{fr}_{b_i}F)(\gamma^m_{b_i})^{-1}$$

Equation 4:

$$A_{s2_i} = (C^{sm}_{s_i} + C^{pe}_{s_i} + C^{fr}_{s_i}F)(\gamma^m_{s_i})^{-1}$$

Equation 5: $A_{b3_{ij}} = a_{b_{ij}} C^{re}_{b_{ij}}$

Equation 6: $A_{s3_{ij}} = a_{s_{ij}} C^{re}_{s_{ij}}$

$a_{b_{ij}}, a_{s_{ij}}$ - coefficients:

Equation 7: $a_{b_{ij}} = \begin{cases} 1 & , j = 1 \\ (\beta^c_{b_{ij}} - d_{b_{ij}})(\gamma^m_{b_{ij}})^{-1} & , j \neq 1 \end{cases}$

Equation 8: $a_{s_{ij}} = \begin{cases} 1 & , j = 1 \\ (\beta^c_{s_{ij}} - d_{s_{ij}})(\gamma^m_{s_{ij}})^{-1} & , j \neq 1 \end{cases}$

The notation of the constants and variables in the Objective Function are given in Table 1 and Table 2 respectively. The formulas use the following indexes: "i" means the time step of the calculation procedures; "j" means the economic metal type produced from the treatment of a given type of ore.

CONSTANT	DEFINITION
n	Number of time periods to be considered
m_b	Number of payable metals from BOT treatment
m_s	Number of payable metals from SOT treatment
d_i	Discount factor - $d_i = (1+r)^{-i}$, where r is the discount rate
$S_{b_{ij}}$	Price of j-th payable metal from BOT treatment
$S_{s_{ij}}$	Price of j-th payable metal from SOT treatment
$C^m_{b_{ij}}$	Unit operating cost of BOT mining
$C^m_{s_{ij}}$	Unit operating cost of SOT mining
$C^p_{b_i}$	Unit operating cost of BOT processing
$C^p_{s_i}$	Unit operating cost of SOT processing
$C^{sm}_{b_i}$	Smelter charge per dry metric ton (DMT) of BOT concentrate
$C^{sm}_{s_i}$	Smelter charge per DMT of SOT concentrate
$C^{pe}_{b_i}$	Penalties per DMT of BOT concentrate
$C^{pe}_{s_i}$	Penalties per DMT of SOT concentrate
$C^{fr}_{b_i}$	Freight charge per wet metric ton (WMT) of BOT concentrate
$C^{fr}_{s_i}$	Freight charge per wet metric ton (WMT) of SOT concentrate
F	Coefficient for transforming WMT into DMT
$C^{re}_{b_i}$	Refining charge per unit of payable metal from BOT treatment
$C^{re}_{s_i}$	Refining charge per unit of payable metal from SOT treatment

CONSTANT	DEFINITION
C^{mil}	Marketing and insurance costs and losses during BOT concentrate transportation as a % of total revenue from selling the payable metals - $C^{mil} = C^{mil}(100\%)^{-1}$
C_{w_i}	Unit operating cost of waste removal
$\beta^c_{b_{ij}}$	Grade of j-th payable metal of dry BOT concentrate
$\beta^c_{s_{ij}}$	Grade of j-th payable metal of dry SOT concentrate
$d_{b_{ij}}$	Grade deduction of j-th payable metal of dry BOT concentrate
$d_{s_{ij}}$	Grade deduction of j-th payable metal grade of dry SOT concentrate
$\gamma^c_{b_i}$	Recovery of the leading payable metal in concentrate obtained from BOT
$\gamma^c_{s_i}$	Recovery of the leading payable metal in concentrate obtained from SOT
$\gamma^m_{b_i}$	Recovery of the leading payable metal in final product from BOT concentrate - $\gamma^m_{b_i} = \gamma^m_{b_{ij}}\Big\vert_{j=1}$
$\gamma^m_{s_i}$	Recovery of the leading payable metal in final product from SOT concentrate- $\gamma^m_{s_i} = \gamma^m_{s_{ij}}\Big\vert_{j=1}$
R_o	Royalty as a % of total revenue from selling the payable BOT metals - $R_o = R_o(100\%)^{-1}$
T	Taxation of the profit from operation activity - $T = T(100\%)^{-1}$
TC_I	Time costs
LIP_I	Loan interest payments
DA_i	Depreciation and amortization allowance
EX_I	Exploration costs
LCF_{i-1}	Losses carried forward
CI_i	Capital investments - $CI_i = CI_i^{min} + CI_i^{eco} + CI_i^{soc}$, where $CI_i^{min}, CI_i^{eco}, CI_i^{soc}$ are the investment costs for mining production, ecological and social purposes respectively
h_{ki}	Unit purchase cost of production capacity of k-th excavator model
u_{ki}	Penalty as average losses from the decrease of total capacity of k-th excavator model
SP_I	Cumulative quantity of BOT in i-th time period
SML_I, SMU_i	Cumulative quantities of the leading BOT & SOT metals for best and worst case corresponding to SP_I
$SBMX_i$,$SBMN_i$	Cumulative quantities of the leading BOT metal for best and worst case corresponding to SP_i
$SSMX_i$,$SSMN_I$	Cumulative quantities of the leading SOT metal for best and worst case corresponding to SP_i
SVL_i, SVU_i	Minimum and maximum cumulative quantity of waste to be removed corresponding to SP_I

Table 1: Objective Function Constants

VARIABLE	DEFINITION
M_{b_i}	Payable leading metal from BOT treatment
M_{s_i}	Payable leading metal from SOT treatment
V_i	Waste quantity to be removed
NC_{ki}	New equipment capacity added for k-th excavator model in the beginning of the i-th period
DC_{ki}	Decrease of total equipment capacity of k-th excavator model in the i-th period

Table 2: Objective Function Variables

The analysis of the Objective Function expression can give the answer to the question about which parameters influence the optimization of the annual metal quantities. Logically there should be the variable costs of all technological processes of the mining, processing and smelting. The marketing costs also influence the metal quantities taking part in the expressions of M_b and M_s. From the taxation parameters only the royalty has a full influence while the profit taxation has the effect of a scaling factor, because it participates in all expressions of the NPV.

The group of the fixed costs (*TC, LIP, DA, EX, LCF, CI*) doesn't have any influence on the optimum assessments of the defined variables because they are treated as constants in accordance with the requirements of the LP technique used. These costs influence only the NPV assessment of the project.

A general conclusion can be made that the optimum metal quantities depend on the variable costs and taxation parameters as well as on the possibilities of the common cumulative graph of the open pit complex which extreme curves are transformed into common upper bound functions. In this connection it should be clarified that the optimization of the annual quantities of the leading payable metal (M_b) is achieved with a fixed BOT production which meets the mill capacity of the processing plant. It means that the BOT production, for which the cumulative representation is known as an Annual Basic Ore Production Function (ABOPF), is fixed in advance. The adoption of such an approach in the optimization of the production scheduling can be explained from a few points of view. First, the process of the exploitation of the open pit complex with a stabilization of its mining rate represents an adequate modeling that aims the effective utilization of the available mining equipment (shovels, trucks). Second, this approach gives bigger possibilities to the short-term planning with the option for varying the BOT metal production in accordance with the existing economic situation. Graphically it is illustrated in Figure 2 for one of the two extreme possible cases for leading the mining operations, where examples of Common Upper Bound Basic Metal Function (CUBBMF), Common Upper Bound Secondary Metal Function (CUBSMF) and ABOPF are presented.

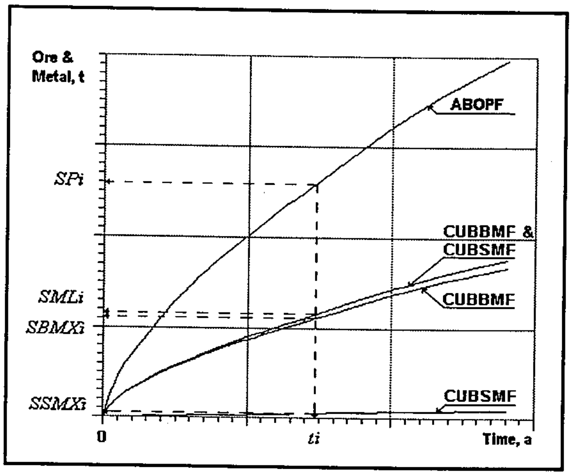

Figure 2: Common Upper Bound Ore & Metal Functions – Best NPV Case

As to the production of the secondary ore type, it is treated as a variable in the optimization model being a derivative of the SOT metal. The cumulative representation of this type of ore production gives the Annual Secondary Ore Production Function (ASOPF).

The constraints of the full LP model are given in [*Halatchev, 1995*].

Case Study

Mining Object of Investigation:

The object of the present investigation is 'Assarel' a copper open pit complex in Bulgaria. The investigation is based on a (*.RES) data file obtained by Four-D. Forty pit shells are generated and they are grouped into three independent pit units as follows: initial pit (1,20); first cutback (21,31); second cutback (32,40). The ore, from a technological point of view, is divided into two ore types: basic ore type (BOT) and secondary ore type (SOT). The BOT is processed in a pressing plant which produces a floatation copper concentrate. The SOT, which is an oxide copper ore, is stockpiled and processed by leaching. The product from the SOT leaching represents another type of copper concentrate. The two types of copper concentrate are supplied to a common smelter for producing economic metals as final products. The floatation copper concentrate contains copper, gold, silver as economic metals.

Computer Implementation:

The computer code FDLT [*Halatchev, 1995*] was used for the case study. The code is applied for calculating the input data of the optimization LP model described above.

The optimization model is run separately by using the popular linear programming solver LINDO (Linear Interactive and Discrete Optimizer).

The Input Data

The data of some more important parameters of the model are given in Table 3.

PARAMETER	VALUE	PARAMETER	VALUE	PARAMETER	VALUE
n	24 years	$\mathrm{C}^{\mathrm{m}}_{\mathrm{s}_{\mathrm{ij}}}$	1.2 $/t	$C^{re}_{b_i}(Ag)$	0.40 $/oz
m_b	3	C_{w_i}	1.65 $/t	$C^{re}_{s_i}(Cu)$	220 $/t
m_s	1	$C^{p}_{b_i}$	3.6 $/t	R_o	3%
r	10%	$C^{p}_{s_i}$	1.6 $/t	T	37%
$S_{b1}(Cu)$	1800 $/t	$C^{sm}_{b_i}$	110 $/dmt	d_{b1}	1%
$S_{b2}(Au)$	300 $/oz	$C^{sm}_{s_i}$	140 $/dmt	d_{b2}	1 g/dmt
$S_{b3}(Ag)$	6 $/oz	$C^{re}_{b_i}(Cu)$	220 $/t	d_{b3}	30 g/dmt
$\mathrm{C}^{\mathrm{m}}_{\mathrm{b}_{\mathrm{ij}}}$	1.2 $/t	$C^{re}_{b_i}(Au)$	4 $/oz	d_{s1}	0.3%

(*) *US dollar currency is used*

Table 3: Input Data of the Optimization Model*

The data of the shovels used are given in Table 4. The ABOPF is presented graphically in Figure 4. The existed mill capacity is 11 million tones.

MODEL OF SHOVEL	NUMBER OF SHOVELS	AVAILABILITY %	ANNUAL PRODUCTION	
			Mean, t	S.D., t
Liebherr 994	2	90	4754650	74381
Dresser 580	1	85	4928205	75652
EKG_8I (Russia)	2	85	3796520	77480
EKG_4I (Russia)	2	80	2401880	64254

Table 4: Data of the Shovels Used

Results

The re-arranged common cumulative graph of the 'Assarel' open pit complex is shown in Figure 3. It represents a relationship between the waste and BOT&SOT leading metals for both extreme cases of leading the mining operations from a purely economic and technological point of view. The graph is not opened because the BOT quantities for these two cases are enough and meet the mill requirement for supplying ore quantities in time corresponding to the ABOPF, which is fixed in advance. The ABOPF reflects the company need of given quantities of final products in the conditions of the present competitive metal market. The leading metal for both ore types is the copper, the quantities of which in the common cumulative graph are calculated taking into account the smelter deductions. The transformation of the curve of the worst NPV case to time gives the common upper bound functions of the waste (CUBWF), basic ore (CUBBOF) and secondary ore (CUBSOF) regarding the ABOPF (Figure 4). The times (t_1, t_2) of the transition commencement of the mining operations from one to another stage are also illustrated in the figure. The CUBBOF is located above the ABOPF that is the proof of the above conclusion of ensuring enough ore quantity to the mill. Figure 5 shows the common upper bound functions of the leading BOT metal for the two extreme cases of leading the mining operations. The analysis of this graph allows the conclusion to be made that despite the fact that the mill works with a constant annual basic ore production of 10 million tones for the period of the normal exploitation of the pit complex, there is an optimization domain between the CUBBMFs of the two extreme cases. The function of the worst NPV case is below the one of the best NPV case, which is a result of the application of the principle of high grading staged in the methodology of Four-D, i.e. the inner pit shells have higher grade than the pit shells at the pit periphery. Due to this principle the function of the best NPV case varies continuously while the other function has a stepped variation. This phenomenon can be explained with the grade distribution for each pit bench. It means that the upper benches of each independent pit unit have a lower grade than the lowest benches. The optimization solution curve of the BOT metal is located within the feasible domain of this graph. Figure 6 shows the same common upper bound functions regarding the SOT metal. There is also an optimization domain in this graph but the functions of both cases don't follow the trends of the BOT metal variation analyzed above. There are three horizontal parts of the function of the worst NPV case, which means that there isn't a SOT metal in the lowest benches of each pit unit of the open pit complex.

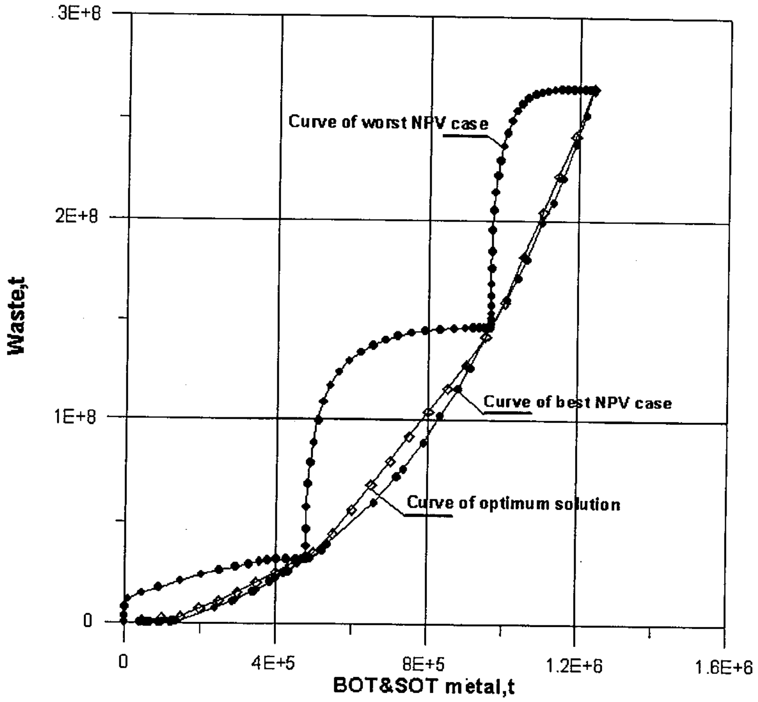

Figure 3: Re-arranged Common Cumulative Graph for 'Assarel' Open Pit complex

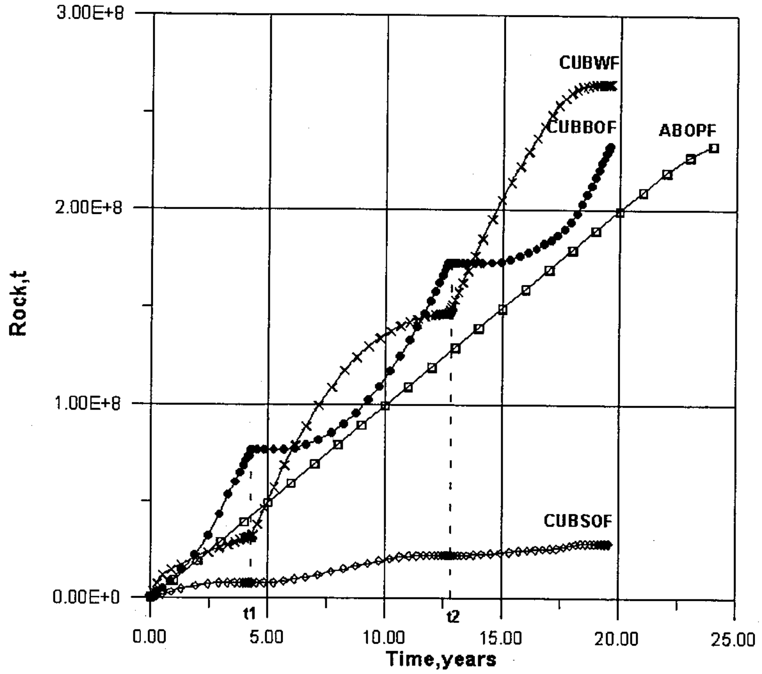

Figure 4: Common Upper Bound functions for 'Assarel' Open Pit complex – Worst NPV Case

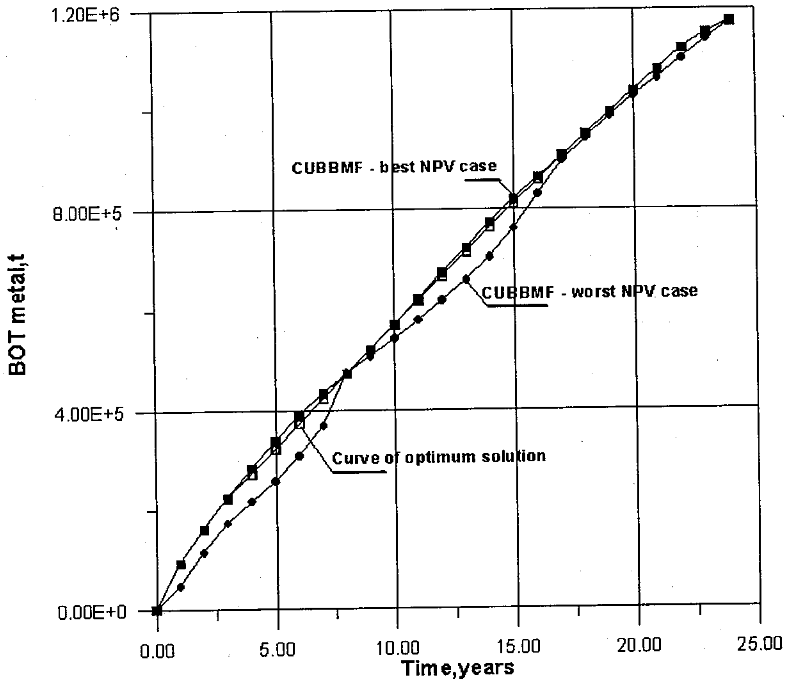

Figure 5: Comon Upper bound Basic Metal functions for the Open Pit Complex

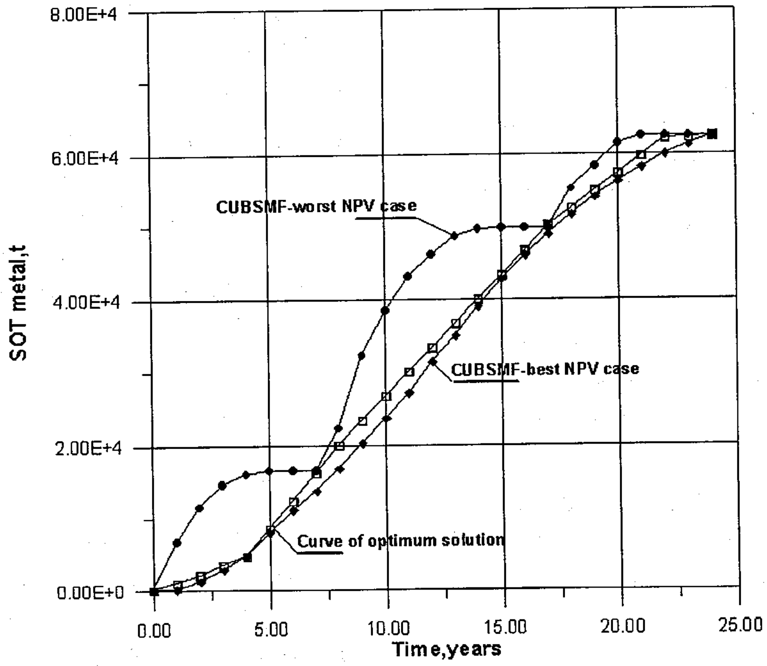

Figure 6: Common Upper Bound Secondary Metal Functions for the Open Pit Complex

Conclusions

1. The mining strategy is a basis of the production scheduling of the open pit complex because it forms the macro-economic framework of its optimization.
2. The model developed provides a direct optimization of the annual quantities of a given economic metal recovered from the ore treatment. It allows the prediction of the metal production required in the context of the application of the supply-demand relationship for determining the value of this product.
3. The optimization model takes into account the whole range of possible real costs of the production process on the basis of a full DCF analysis of the mining project.
4. The sphere of the model application covers the deposits of polymetallic ore, which can have an unlimited number of economic metals.
5. The approach suggested for optimizing the production scheduling of an open pit complex ensures flexible realization of the mining strategy accounting for the constantly changing conditions of the international base metals market.

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