Production Scheduling and Mine Fleet Assignment Using Integer Programming

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF TECHNOLOGY

IN

MINING ENGINEERING

BY

ASHISH KUMAR

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NATIONAL INSTITUTE OF TECHNOLOGY
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CERTIFICATE

This is to certify that the thesis entitled "**Production Scheduling and Mine Fleet Assignment Using Integer Programming"** submitted by Sri ASHISH KUMAR (Roll No. 110MN0496) in partial fulfillment of the requirements for the award of Bachelor of Technology degree in Mining Engineering at the National institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in this thesis has not formed the basis for the award of any Degree or Diploma or similar title of any university or institution.

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ABSTACT

Production Scheduling, extraction sequence of mining blocks in different production periods to maximize profit over the life of the mine and subjected to different constraints, is an important aspect of any mining activity. Mine production scheduling problem can be solved using various approaches, but the best approach is one which can give an optimal result. Production scheduling solely cannot result in a proper planning thus, fleet assignment problem needs to be incorporated into production scheduling problem to have a realistic mine plan. Proper fleet assignment ensures that the fleet is not under or over utilized. Fleet assignment problem is integer type programming since, size of fleet cannot be a floating number. In this thesis, production scheduling and fleet assignment problem are solved using branch and cut algorithm. Production schedule for 4736 blocks from a case study of coal mine is done with a production period of 5 years. Solution time for solving the production scheduling problem was 48.14 hours with an NPV value of Rs 4.45938×10^{11}. Short terms production scheduling is done for one year and the NPV value obtained was Rs 7.59796×10^{10} with a solution time of 57.539 minutes. Fleet assignment is done for first year and is observed that the size of dumper fleet can be reduced to 30 thus saving huge amount of initial capital investment.

CHAPTER-I

Introduction

I.I Introduction

Mine production scheduling consists of solving three different problems viz. sequencing of extraction of blocks, decision regarding destination of these blocks and production requirements (Hochbaum and Chen, 2000; Caccetta and Hill, 2003; Kumral and Dowd, 2005;Saring and West-Hansen,2005). However there are certain other aspects such as mine fleet assignment which need to be incorporated with mine production scheduling. Thus there is a dilemma that different sub problem needs to be solved before solving mine production scheduling. In other words, production scheduling and mine fleet assignment is interdependent problems (Kumral and Dimitrakapoulos, 2012). Many researchers have devoted their efforts to solve fleet assignment problem like selection of excavation equipment by minimizing the time required for excavation of a bench using integer programming (Michiotis et al, 1998), mixed integer programming for scheduling a fleet of mining trucks such that maintenance cost is minimized (Topal and Ramazan, 2010). Elbrond and Sournis, (1987) developed a relation between production scheduling and fleet assignment. Since both the problems are inter-related with each other and one sub problem should be solved before solving the other therefore there is a need of solving both the problems viz. production scheduling and fleet assignment. Since solving both the problems together is computationally expensive, a sequential solution approach was developed for production scheduling and fleet assignment problem. In this thesis, the production scheduling problem was solved first and then using the results fleet assignment problem was solved.

I.II Objectives of the Project

This thesis has been broadly classified into five different parts. Literature of different parts has been discusses in Chapter II. Various terminologies used all through the project is discussed in Chapter II itself. The different objectives are:-

1. Scheduling the mining production over the life of mine in order to develop the desired working locations using Branch and Cut algorithm. Production planning is done for long term and short term. Long term planning is done for a period of 5 years while short term planning is done for 1 year with a period of three months.

2. Optimizing the hauling parameter which include, optimizing the fleet size of dumpers for different faces (Production and Overburden).
3. Optimizing the loading parameter which include, optimizing the fleet size of the shovel and loader and also finding the appropriate use of the different loading equipment's for different faces.

I.III Phase of Project

Various literature and terminologies regarding this thesis work is discussed in chapter II. First phase of thesis deals with detailed description of the block model and generation of three dimensional array of blocks using ordinary kriging method (Isaak & Srivastava 1990) is in Chapter III.

Second phase proceeds towards developing an optimum schedule for the mining project. Branch and cut algorithm is used to solve production planning problem and an optimum schedule is generated for a period of 5year and a short term schedule is generated for one year. The final approach of this project is to find the fleet size such that total operating cost is minimum. Detailed problem and description can be found out in Chapter III.

Geological description of the deposit is described in Chapter IV which also includes, various other information about the project and a brief description of the mine. Also the number of various fleet available and value of different parameters used in this thesis work is described and mentioned in Chapter IV. Results from the case study taken under this thesis work is dealt in chapter V.

CHAPTER-II

Literature Review

II.I Introduction

Production scheduling problem is an integer programming problem with linear objective function and constraints, and decision variables takes binary values. Sometimes, the decision variables of production scheduling can also be real values which is a typical example of mixed integer programming.

II.II Production Scheduling

Production scheduling problem is solved using either integer of mixed integer programming to maximize the net present value as an objective function. Net present value is defined as the value of the different payments in different periods brought into present scenario (Hustrid and Kuchta, 2006).

Production scheduling problems is solved using different approaches such as using linear programming and integer programming (Barbaro and Ramani, 1986), dynamic programming (Mukherjee, 1994). Caccetta and Hill (2003) developed a branch and cut algorithm for mine production scheduling; whereas, Bley et al. (2010) proposed a cutting plane technique for solving same type of problem. Branch and cut algorithm basically runs a branch and bound algorithm (general algorithm for finding optimal solution to various optimization problems) and uses cutting planes to tighten the linear programming relaxations (Padberg and Rinaldi, 1991). The major limitation with exact methods is that they can only be applied to instances of relatively small size of problem. Solving instances of realistic size, where typically the number of blocks is in the order of tens to hundreds of thousands, requires prohibitive computational times. To reduce the size of the problem and thus make large instances of practical interest computationally tractable by exact methods, Ramazan (2007) exploits the structure of the problem to aggregate blocks into groups using spanning tree algorithm. Other approaches to tackling realistic large-scale instances rely on heuristics (Gershon, 1987), a combination of dynamic programming and heuristics (Tolwinski and Underwood, 1996), genetic algorithms (Denby and Schofield, 1994), and particle swarm algorithms (Ferland et al., 2007). A more detailed review of the different solution approaches for the mine production scheduling problem can be found in (Newman et al. 2010). Optimization problems that arise in the mining context such as fleet allocation was also review in these papers

(Souza et al., 2010; Topal and Ramazan, 2010). The deterministic version of the mine production scheduling problem ignores the uncertain nature of the problem, which leads to misleading assessments (Ravenscroft, 1992; Dowd, 1994; Dimitrakopoulos et al., 2002; Godoy and Dimitrakopoulos, 2004).

II.III Mine Fleet Assignment

Mine fleet assignment problems aims at selecting the appropriate numbers of trucks and loading equipment subjected to various objectives and constraints (Burt, 2008). Constraints and objective function varies from mine to mine. There are different methods available to solve the problem such as, heuristic method, statistical methods, optimization techniques, simulation, and artificial intelligence.

II.III.I Heuristic Method

The use of heuristic methods persists in industry, with spreadsheets employed to aid iteration rather than optimization (Eldin and Mayfield, 2005). Smith et al. (2000) recommended the construction industry darling match factor formula as a means of determining the appropriate fleet size. Match factor ratio published by (Morgan and Peterson, 1968) is restricted to homogenous fleet and (Burt and Caccetta, 2007) to heterogeneous truck fleets. The flow chart described in Figure 2.1 illustrates the techniques used by equipment selectors. However, it relies heavily on one or more experts in equipment selection thus increases the likelihood of an attractive alternative being missed in the process of selection (Webster and Reed, 1971).

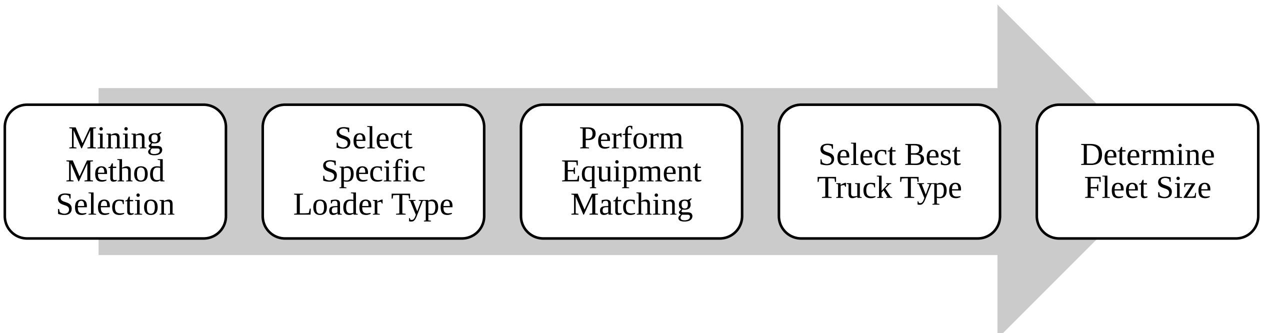

Figure 2.1 Classical equipment selection heuristic (Burt, 2008)

II.III.II Statistical Methods

Blackwell (1999) developed a multiple linear regression model to predict the important equipment selection parameters that displays great variation, such as truck cycle time, tire consumption, fuel consumption and truck operating hours. The results shows that these parameters are estimated via simulation with questionable results due to variations in truck power and load carried. These parameters can then be used to govern an appropriate fleet of trucks and loaders through the use of the simple match factor heuristic above or other means. This method relies on the existence of large data sets for the appropriate parameters for the mine in question. A heuristic method for determining the truck fleet size using queuing theory was developed. This extended the work by (O'Shea, 1964) for calculating the productivity of a set of feet options by estimating the truck arrival rates by Poisson distribution. Later, Farid and Koning (1994) used simulation to verify the equipment selection results of a queuing theory based on the O'Shea works.

II.III.III Optimization Techniques

Integer programming for mining and construction industry for fleet assignment (Jayawardane and Harris, 1990). Integer programs have been also used to create mining schedules (Dagdelen et al., 2000, Dagdelen and Asad 2002; Johnson, et al., 2002; Ramazan and Dimitrakopoulos, 2003; Kumral and Dowd, 2005) and for pit optimization (Caccetta and Hill, 2003). However, for equipment selection focuses on project completion and dispatching, allocation (Ercelebi and Kirmanli, 2000). The models tend to assume given equipment types, rather than allowing the models to select these with the fleet size. Fleet homogeneity and restricted passes between loader and truck are also common constraints (Celebi, 1998) that have not been demonstrated to be sensible. In a departure from cost optimization, some solution methods look at optimizing productivity (Smith et al., 2000) and optimizing equipment matching (Morgan, 1994b). Since maximizing productivity is different to minimizing cost, such objectives are also useful in the construction industry. For example, in other formulations, budgeting constraints have been considered where the maximum permissible budget cash outlay for a given time period is an upper bound (Cebesoy et al., 1995). Mutual exclusivity is a common restriction that only allows one type to be used. Cebesoy et al. (1995) describes heterogeneous fleets as unacceptable or even unthinkable, although only anecdotal evidence has supported these claims to date. Cohen et al.,

(2006) presented an efficient approximation for the generalized assignment problem based in novel combinatorial translation of any algorithm.

II.III.IV Simulation

Simulation is a powerful tool for mining industry (Hall 2000). Large set of data is used for simulation in order to train a neural network for prediction production by machinery (Shi 1999). Interaction of particular equipment's can be observed by using simulation. (Schexnayder et al., 2005) describes a simulation model for predicting productivity. Thus simulation can also be used to estimate a suitable cycle time (Frimpong et al., 2003).

II.III.V Artificial Intelligence

Decision support system methods (Bandhopadhyay and Venkatasubramanian, 1987) and genetic algorithms (Haidar and Naoum, 1995). Ganguli and Bandopadhyay (2002) developed a system which requires the user to input relative importance of the factor for equipment selection. However it is difficult to estimate and quantify the relative importance of different factors. Naoum and Haidar (2000) developed a genetic algorithm for equipment selection. Marzouk and Moselhi (2004) designed a bold model to minimize two objectives simultaneously i.e. time and cost using simulation and genetic algorithm.

CHAPTER-III

Project Development

III.I Introduction

The project is developed from the baseline data i.e. Borehole data. Project development is done in following phases:-

1. Development of block model using geostatistical method (Isaak and Srivastava, 1990).
2. Formulation of scheduling problem
3. Formulation of fleet assignment problem

Each and every phase of the project development is described in detailed later in this chapter. However the solving technique and the relevant justification is mentioned in chapter V where case study of mine is used to solve the formulation presented in this thesis work.

III.II Reserve Estimation

Incessantly increasing production requirement from various steel and power industries is forcing the mining industry to increase the production manifold. Thus it requires a proper estimation of resource and technically sound mine plan to meet the production requirement. Estimation of reserve can be done using various geostatistical method available such as ordinary kriging, simple kriging, triangulation method, nearest neighborhood method, inverse distance method, and polygonal method (Isaak and Srivastava, 1990). However ordinary kriging method is unbiased method thus gives an accurate result (Isaak and Srivastava, 1990). Kriging method requires formulation of variogram (Isaak and Srivastava, 1990).

III.III Production Scheduling

Production scheduling for opencast mine is done in order to determine which blocks to be extracted in which period such that the total profit generating from the mine is maximum, considering the whole life of mine. If the schedule is proper than mining companies can extract the ore at least possible cost by handling the minimum waste. Scheduling can be performed using different algorithm available and with different software available, but the most important task of scheduling is to perform it within time period feasible. If the number of blocks increases then the computational time for solving those problem increases highly. Thus we need to determine a feasible method so as to solve the problem within a time period specified.

Production scheduling problem is formulated with objective function as maximization of NPV (Net Present Value) and subject to following different constraint as mining ore and waste constraint, grade constraint, reserve constraint, slope constraint.

III.III.I Complete Model

Production scheduling problem is formulated with NPV maximization as the objective function and subjected to different constraints.

Maximize

$$\sum_{i=1,t=1}^{N,T} C_{i,t} * x_{i,t} \qquad (I)$$

Subjected to:-

$$\sum_{n=1,t=3}^{N,T} x_{i,t} * g_i * T_i \ \leq g_{max} * M_{max} \qquad (\ II)$$

$$\sum_{n=1,t=3}^{N,T} x_{i,t} * g_i * T_i \ \geq g_{min} * M_{min} \qquad (III)$$

$$\sum_{n=1,t=3}^{N,T} x_{i,t} * T_i \ \leq M_{max} \qquad (IV)$$

$$\sum_{n=1,t=3}^{N,T} x_{i,t} * T_i \ \geq M_{min} \qquad (V)$$

$$\sum_{t=1,n=1}^{T,N} x_{t,i} \ \leq 1 \qquad (VI)$$

$$\sum_{w=1,n=1}^{T,N} x_{w,i} - \sum_{t=1}^{w} x_j \ \leq 1 \qquad (VII)$$

Variables:-

$x_{i,t} \in \{0, 1\}$, value of $x_{i,t}$ is 1 if the block is extracted in period t and 0 otherwise

Where j ∈ $predecessor\ of\ i$

$$C_{i,t} = \frac{(C_i)}{(1+r)^{t-1}} \qquad (VIII)$$

(C_i) = Block Economic Value of block i

N = Number of total blocks

T = Total time period of scheduling

M_{max} = Maximum Mining Quantity

M_{min} = Minimum Mining Quantity

g_{max} = Maximum Grade

g_{min} = Minimum Grade

Production scheduling problem is a integer programming problem. Objective function makes sure that the NPV value of the profit is maximum, while maintaining the different constraints of grade and production. In this equation $C_{i,t}$ is the BEV (Block Economic Value) of different blocks, and is brought to net present value, r is the discount rate at which the value is brought back. Thus for the given scenario, first year production will have no change in there BEV, but from the next year onward the NPV changes according to the discount rate. The problem is done for a period of 5 years. After the process of long term production scheduling the result is used to get a short term production planning. Thus we will have a long term production plan for per year wise and a short term production plan per month wise.

1. Grade Constraint

$$\sum_{n=1,t=3}^{N,T} x_{i,t} * g_i * T_i \leq g_{max} * M_{max}$$

This constraint ensures that the cumulative grade of the extracted ore is not more than highest grade of ore required.

$$\sum_{n=1,t=3}^{N,T} x_{i,t} * g_i * T_i \geq g_{min} * M_{min}$$

This constraint ensures that the cumulative grade of the extracted ore is more than the cutoff grade value. R.H.S of the equation ensures that the grade of the extracted ore is less than the cutoff grade specified for the mine from the power plant. This constraint is must for the mining industry because it will directly impact on the profit generated from the overall operation. If the grade is lower than the cutoff grade than the material is treated as waste. Thus it is necessary to ensure that the cumulative grade of the extracted material in a period is more than the cutoff grade.

2. Production Constraint

$$\sum_{n=1,t=3}^{N,T} x_{i,t} * T_i \leq M_{max}$$

$$\sum_{n=1,t=3}^{N,T} x_{i,t} * T_i \geq M_{min}$$

Production constraints are defined to ensure that the production targets are within a range, so that there will be no issue of short of production and excess of production. Both of these situations creates problem for the industry. Two equations ensures that the production is not less than the desired value and not greater than the value which can be accommodated within the stockpile.

3. Reserve Constraint

$$\sum_{t=1,n=1}^{T,N} x_{t,i} \leq 1$$

Reserve constraints are defined to ensure that the blocks are extracted in one and only one period. Since one block cannot be extracted in more than one period thus this constraint with R.H.S ensures that the value of L.H.S is such that the blocks are not extracted in more than one period.

4. Slope Constraint

$$\sum_{w=1,n=1}^{T,N} x_{w,i} - \sum_{t=1}^{w} x_j \le 1$$

This constraint ensures that a block is extracted only if blocks falling at a slope of 45^0 above is extracted. This constraint ensures that block are extracted in a sequence i.e. the block at the upper layer is extracted first then the blocks below it.

III.IV Mine Fleet Assignment Problem

Mine fleet Assignment problem is a vast problem and needs to be solved in order to minimize the overall operating cost of the machinery. Also proper mine fleet assignment helps to save time and energy needed to haul material. Proper mine fleet assignment also ensures that the production demands are fulfilled as per need of the plant. Thus this problem possess great challenge to be optimized. Different constraints used for formulating the fleet assignment problem are hauling ore and waste constraint, loading ore and waste constraint, equipment compatibility constraint, equipment reserve constraint.

III.IV.I Complete Model

In this thesis work fleet assignment problem is done based on minimizing the objective i.e. minimizing the operating cost subjected to different constraints.

Minimize

$$\sum_{i,j}^{M,N} C_D * \left(x_{c,e,i} + x_{o,e,j}\right) + C_S * \left(x_{e,i} + x_{e,j}\right) + C_L * \left(x_{L,i} + x_{L,j}\right) \qquad (IX)$$

Subjected to:-

$$\sum_{i,j}^{M,N} x_{c,e,i} + x_{o,e,j} \le TD \qquad (X)$$

$$\sum_{i,j}^{M,N} x_{e,i} + x_{e,j} \le TS \qquad (XI)$$

$$\sum_{i,j}^{M,N} x_{L,i} + x_{L,j} \leq TL \qquad (XII)$$

$$\sum_{i}^{M} \frac{x_{e,i} * a_e * c_e * S.G_c * 3600}{T_e} + \frac{x_{L,i} * a_L * c_L * S.G_c * 3600}{T_L} \geq T_c \qquad (XIII)$$

$$\sum_{j}^{N} \frac{x_{e,j} * a_e * c_e * S.G_o * 3600}{T_e} + \frac{x_{L,j} * a_L * c_L * S.G_o * 3600}{T_L} \geq T_o \qquad (XIV)$$

$$\sum_{i}^{M} \frac{x_{c,e,i} * a_D * c_D * 3600}{T_{c,e,i}} \geq T_c \qquad (XV)$$

$$\sum_{j}^{N} \frac{x_{o,e,i} * a_D * c_D * 3600}{T_{o,e,j}} \geq T_o \qquad (XVI)$$

$$\sum_{i}^{M} \frac{x_{c,e,i} * a_D * c_D * 3600}{T_{c,e,i}} \geq \sum_{i}^{M} \left(\frac{x_{e,i} * a_e * c_e * S.G_c * 3600}{T_e} + \frac{x_{L,i} * a_L * c_L * S.G_c * 3600}{T_L}\right)$$

(XVII)

$$\sum_{j}^{N} \frac{x_{o,e,i} * a_D * c_D * 3600}{T_{o,e,j}} \geq \sum_{j}^{N} \left(\frac{x_{e,j} * a_e * c_e * S.G_o * 3600}{T_e} + \frac{x_{L,j} * a_L * c_L * S.G_o * 3600}{T_L}\right)$$

(XVIII)

Where,

M = Number of total coal block

N = Number of total overburden block

i = Coal face

j = Overburden face

C_D = Cost of operating dump trucks per hour

C_S = Cost of operating shovel per hour

C_L = Cost of operating loaders per hour

$x_{c,e,i}$ = Number of dump trucks assigned to coal face

$x_{o,e,j}$ = Number of dump trucks assigned to overburden face

$x_{e,i}$ = Number of excavators assigned to each coal face

$x_{e,j}$ = Number of excavators assigned to each overburden face

$x_{L,i}$ = Number of loaders assigned to each coal face

$x_{L,j}$ = Number of loaders assigned to each overburden face

T_o = Tonnage that should be removed per hour

T_c = Tonnage requirement of coal per hour

c_D = Capacity of dump trucks in tons

c_e = Capacity of shovel in m^3

c_L = Capacity of loaders in m^3

a_e = Availability of shovel

a_D = Availability of dump trucks

a_L = Availability of loaders

$S.G_o$ = Specific gravity of overburden in $\frac{tons}{m^3}$

$S.G_c$ = Specific gravity of coal in $\frac{tons}{m^3}$

T_e = Cycle time of shovel

T_L = Cycle time of loaders

$T_{c,e,i}$ = Cycle time of dump trucks from excavator to stockpile in sec

$T_{c,e,j}$ = Cycle time of dump trucks from excavator to dumping site in sec

TD = Total number of dumpers available

TS = Total number of shovel available

TL = Total number of loaders available

Variables:-

$x_{c,e,i}$,$x_{o,e,j}$, $x_{e,i}$, $x_{e,j}$, $x_{L,i}$,$x_{L,j}$ are the variables whose values needs to be determined. It represents the number of different fleet which need to be assigned.

Different constraints which are formulated in this project are based on the condition of mine and their requirements. Thus these constraints are formulated likewise.

1. Equipment Reserve Constraint

$$\sum_{i,j}^{M,N} x_{c,e,i} + x_{o,e,j} \leq TD$$

$$\sum_{i,j}^{M,N} x_{e,i} + x_{e,j} \leq TS$$

$$\sum_{i,j}^{M,N} x_{L,i} + x_{L,j} \leq TL$$

This constraint ensures that the maximum numbers of fleet that is assigned is not more than that of available equipment. Maximum number of shovels, loaders and dumpers that can be assigned to different faces shall be a maximum of five, two and thirty nine respectively. This constraint helps in utilization of the resources to maximum.

2. Loading Constraint

$$\sum_{i}^{M} \frac{x_{e,i} * a_e * c_e * S.G_c * 3600}{T_e} + \frac{x_{L,i} * a_L * c_L * S.G_c * 3600}{T_L} \geq T_c$$

$$\sum_{j}^{N} \frac{x_{e,j} * a_e * c_e * S.G_o * 3600}{T_e} + \frac{x_{L,j} * a_L * c_L * S.G_o * 3600}{T_L} \geq T_o$$

This constraint ensures that the loading capacity of the assigned fleet is more than the required productivity of the mine. Thus this constraint ensures that the cumulative loading equipment capacity for total number of equipment's assigned is not undermined.

3. Hauling Constraint

$$\sum_{i}^{M} \frac{x_{c,e,i} * a_D * c_D * 3600}{T_{c,e,i}} \geq T_c$$

$$\sum_{j}^{N} \frac{x_{o,e,i} * a_D * c_D * 3600}{T_{o,e,j}} \geq T_o$$

This constraint ensures that the hauling capacity of the assigned fleet is more than the required productivity of the mine. Thus this constraint ensures that hauling equipment is capable of producing the desired production within stipulated time frame. It also ensures that the production requirement are not less than the desired production rate.

4. Equipment Compatibility Constraint

$$\sum_{i}^{M} \frac{x_{c,e,i} * a_D * c_D * 3600}{T_{c,e,i}} \geq \sum_{i}^{M} \left(\frac{x_{e,i} * a_e * c_e * S.G_c * 3600}{T_e} + \frac{x_{L,i} * a_L * c_L * S.G_c * 3600}{T_L}\right)$$

$$\sum_{j}^{N} \frac{x_{o,e,i} * a_D * c_D * 3600}{T_{o,e,j}} \geq \sum_{j}^{N} \left(\frac{x_{e,j} * a_e * c_e * S.G_o * 3600}{T_e} + \frac{x_{L,j} * a_L * c_L * S.G_o * 3600}{T_L}\right)$$

Equipment compatibility constraint ensures that the cumulative productivity of total dumpers is more than that of the productivity of loading equipment. Thus this constraint ensures that the loading equipment is not underutilized and thus the idle time of shovel is very less.

CHAPTER-IV

Case Study of Opencast Coal Mine

IV.I Introduction

This chapter deals with the detailed geology of the area and the brief description about the mining project. The area lies in Singrauli Coalfield and has the highest potential for production of coal with a present production capacity of 48 MT. About 96 % of the Singrauli coalfield occurs in the state of Madhya Pradesh, in the Sindhi/Singrauli districts. The remainder (4 %) of the coalfields comes under Sonebhadra District, Uttar Pradesh. Different phases of exploration activities have been done in order to determine the resource available within the area.

IV.II Geological Structure

In the present mining block consisting of two blocks Block I and Block II, the southern part which mainly comes in Block II is structurally distributed whereas the northern part of the Block I is free from geological disturbances. There are altogether 11 faults in the southern part of which six have continued from adjoining Block III. The beds have an almost E-W strike in the eastern part which swings NW-SE in the southern part and gradually becomes almost N-S in the northern part. The synclinal axis passes roughly in NE-SW direction. The dips are northerly, north-easterly and easterly in relation to swings in strike. The undisturbed northern property has gentle dips of about 2° to 3°. In the southern part the gradient in general is steeper than northern part. In the remaining part of the southern property the gradient generally varies from 3° to 5°.

IIV.III Sequence of Coal Seams and Parting

Sequence of coal seams and parting as worked out on the basis of the sub surface data obtained through drilling in the present mining block is given in Table 4.1.

Table 4.1 Sequence of Coal Seams and Parting

Coal Seam/ Parting	Minimum Thickness	Maximum Thickness	Average Thickness	No of Borehole Intersection
Seam I	19.50	26.15	22.72	66
Parting	51.97	68.70	61.89	87
Seam II	12.30	19.30	15.91	134

IV.IV Mine and Equipment Description

The mine is located in Singrauli district and the planned capacity of mine is 48 Million Tons Per Annum (MPTA). The end use of coal is by Power Plant (4000 MW) with a grade requirement of G6 to G12. There are two extractable seams and the total life of mine is 30 years. Opencast mining method is used for extracting this deposit with the combination of Shovel and Dumper. However the extraction of coal is done through FE (Front End) and Dumper combination. The list of available equipment available within the mine is mentioned in Table 4.2.

Table 4.2 Equipment-Numbers and Their Capacity

Sl. No	Name of Equipment	Numbers	Capacity
1.	RBH Drill	04	311mm
2.	RBH Drill	08	250mm
3.	RBH Drill	04	160mm
4.	Electric Rope Shovel	06	$42m^3$
5.	Dumper	39	240 ton
6.	Front End Loader	02	$43m^3$

Figure 4.1 Parking Area of Machinery

Figure 4.1 represent the parking stand of machinery used in the mine. Some of the salient features of the project that must be fulfilled while mining is mentioned in the Table 4.3.

Table 4.3 Salient Features of the Project

Sl. No.	Contents	Description
2.	Target capacity of Mine	Minimum -48 MTPA (Million Tons Per Annum) Maximum – 60 MPTA (Million Tons Per Annum)
5.	Grade of Coal	G6 to G12
6.	Stripping Ratio	4.5

IV.V Loading & Hauling Operation

In the current mining project shovels and loaders are used for the purpose of loading the materials into dump trucks. Electric Rope Shovel of Bucyrus Company is used in the present mining project with a bucket capacity of 42 m^3 and Front End Loader of 43 m^3 bucket capacity is used in the present mining project. Different machinery being used currently in the mine for loading purpose is shown in Figure 4.2. Hauling operation is performed by dump trucks of capacity 240 ton. Both the overburden and coal dump trucks are equal in capacity but the design of coal dump trucks is a bit wider to accommodate the required tonnage.

(a) (b)

Figure 4.2 Front End Loader-Dumper combination (b) Shovel-Dumper combination being used in the current mining project

Figure 4.3 Bucyrus MT 4400AC Dump Truck of capacity 240 tons used in the mine

IV.VI Block Economic Value Calculation

Block Economic Value is described as the net profit that will be generated if the specific block is extracted. The basic equation of BEV is defined as:-

$$BEV = Revenue - Cost \quad (XIX)$$

Discount rate is defined as the rate at which future worth of any sum is brought back to present value (Hustrid & Kuchta 2006). The block economic value is calculated for each block using different values as mentioned below:-

1. Specific Gravity
    a. For Waste – 2.16 Ton/m^3
    b. For Coal – 1.16 Ton/m^3
2. Selling Price for Coal from the company data.

Table 4.4 Price of coal w.r.t its GCV

GCV GR	GCV Range (Kilo Calories per Kg)	Basic Rom price for Power Utilities (Rs)
G1	Above 7000	4680
G2	6701-7000	4480
G3	6401-6700	4390
G4	6101-6400	4340
G5	5801-6100	3319
G6	5501-5800	2360
G7	5201-5500	1840
G8	4901-5200	1700
G9	4601-4900	1500
G10	4301-4600	1400
G11	4001-4300	1130
G12	3701-4300	910
G13	3401-3700	690
G14	3101-3400	610
G15	2801-3100	510
G16	2501-2800	474
G17	2201-2500	420

3. Extraction Cost
    a. For Coal – 613.48 Rs/Ton
    b. For Waste - 41.3 Rs/Ton
4. Tonnage for block is calculated based on the size of block and its specific gravity

IV.VII Reserve Estimation

A solid model of the deposit was generated as shown in the figure 4.4. Block economic value was calculated based on the attribute, calorific value assuming other attributes are constant thus, and 190 borehole data are composited for length of 5m and calorific value as an attribute (Isaak and Srivastava, 1990). Statistics of composited data is shown in Figure 4.5. Variogram modeling is done for attribute calorific value and the variogram is shown in Figure 4.6.

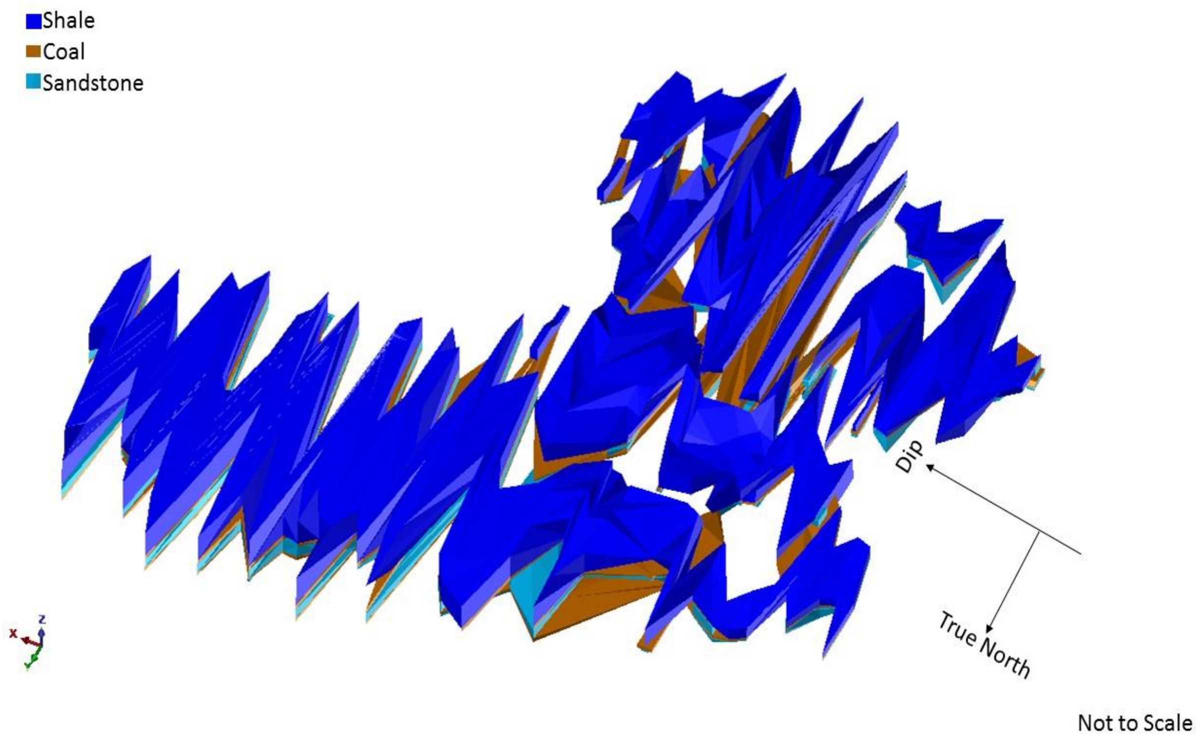

Figure 4.4 Solid model of the deposit

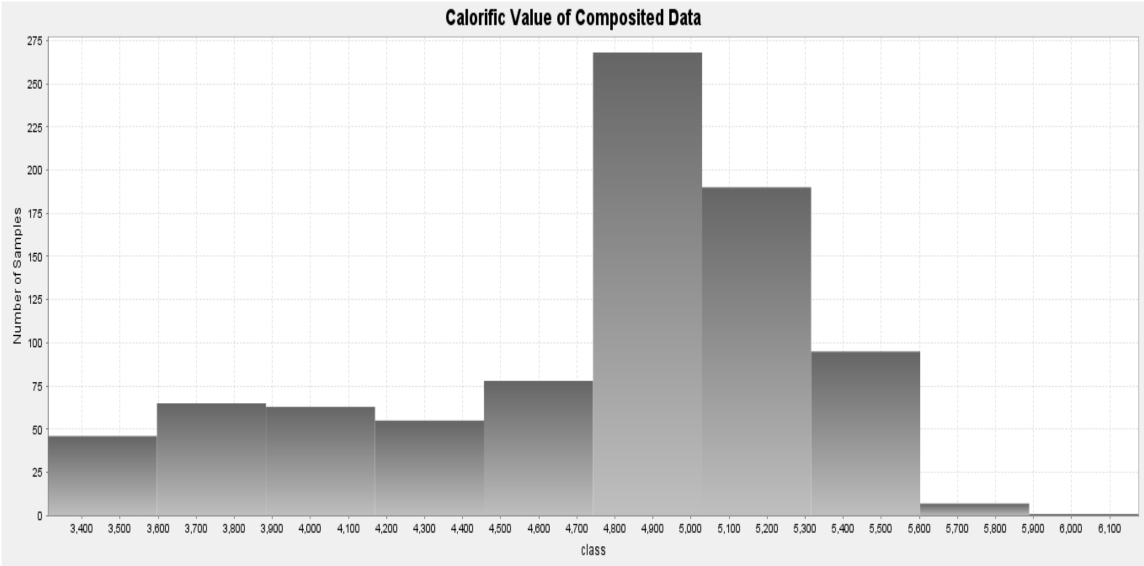

Figure 4.5 Statistics of composite with calorific value as attribute and over 5m length

Experimental variogram is computed for a lag distance of 130 m and maximum distance of 3200. Spherical variogram modeling is fitted on the experimental variogram with a nugget value of 0, sill value of 277249.9 and range of 401.156m.

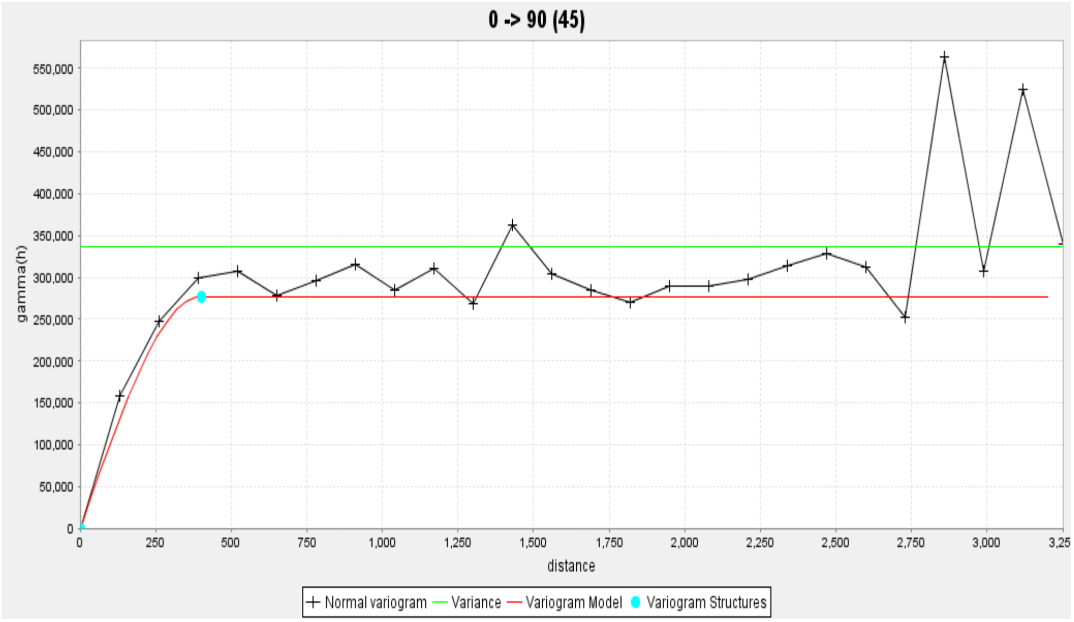

Figure 4.6 Variogram model for major axis

It can be seen from the Figure 4.6 solid model that the different geological formations are in order with Shale at the top and Sandstone layer between two Coal layers.

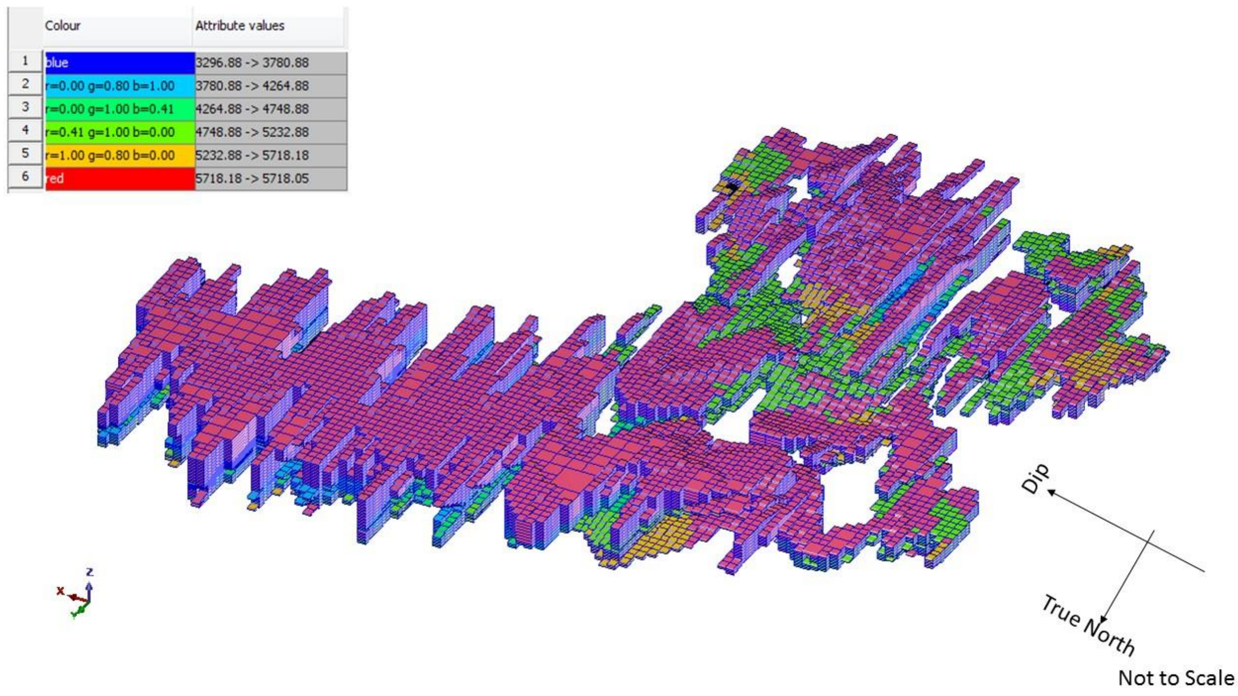

Figure 4.7 Block model of the deposit

Reserve estimation is done using ordinary kriging method and he block model thus obtained after doing reserve estimation is shown in Figure 4.7. Block size for the deposit is taken as 100x100x20 m^3. Thus the total volume of ore above the cutoff grade is 1002.182 MT with an average grade of 4714 Kcal/Kg.

IV.VIII Production Scheduling

Production scheduling for long term is done with following parameters specific to the present case study of mine:-

- Production Requirement/Year (Min) = 48 MT
- Production Requirement/Year (Max) = 60 MT
- Number of Periods = 5
- Minimum Grade Requirement = 3701 Kcal/Kg
- Maximum Grade Requirement = 5800 Kcal/Kg

- Stripping Ratio = 4.5
- Discount Rate = 0.10

For short term production scheduling following parameters is taken into consideration based on the present case study:-

- Production Requirement/period (Min) = 4.8 MT
- Production Requirement/period (Max) = 5.985 MT
- Number of Periods = 10
- Minimum Grade Requirement = 3701 Kcal/Kg
- Maximum Grade Requirement = 5800 Kcal/Kg
- Stripping Ratio = 4.5
- Discount Rate = 0.0259525

IV.IX Mine Fleet Assignment

Fleet assignment problem is solved for one short term period. Cycle time between different faces and destination is calculated using the data mentioned below:-

- Spotting Time = 52.15 sec
- Dumping Time = 60.69 sec
- Velocity travelling up gradient = 8.88 m/s
- Velocity travelling down gradient = 8.33 m/s

The truck cycle time comprises of load time, haul time (full), dump time, return time (empty), queuing and spotting time. A cycle may begin at a loader where the dump-truck receives its load. The truck then travels full to the dump site via a designated route along a haul road. The dump-site can be a stockpile, dump-site or a crushing point. Once the load has been dumped, the truck turns around and travels empty back to the loader or excavator. The act of maneuvering the truck under the excavator is termed as spotting time. This can take several minutes depending upon the nearby features. The truck cycle time is measured from the time the dumper is filled at the excavator **(Load Time)**, travels full to the dump-site **(Haul Time (Full))**, dump the load **(Dump Time)**, and travels empty back **(Return Time (Empty))** to the excavator to join a queue **(Queuing**

Time) and position itself for the next load **(Spotting Time)**. The dumper cycle time includes queuing and waiting times at the dump-site and excavator.

Different parameters taken for the problem formulation of fleet assignment based on the current case study are:-

- Total number of dumper available = 39
- Total number of shovel available = 5
- Total number of loaders available = 2
- Production requirement of ore = 4438 tons/hr.
- Amount of overburden to be displaced = 6873 tons/hr.
- Cycle time of shovel = 90sec
- Cycle time of loader = 95 sec
- Cost of operating dumpers = 6160 Rs/hr.
- Cost of operating shovel = 1334888.33 Rs/hr.
- Cost of operating loaders = 25610.66 Rs/hr.

Coordinates of different location i.e. stockpile and dump is used in Table 4.5 to calculate the cycle time. Cycle time is calculated based on the formula mentioned in chapter II. This cycle time is used as input parameter for the optimization process. For doing fleet assignment availability of different equipment is also taken into account as mentioned in Table 4.6. Availability of different equipment is calculated from one year previous data.

Table 4.5 Location data of stockpile and dump

Location	**X**	**Y**	**Z**
Stockpile	-20912.9	-1165.35	-187.88
Dump	-19303.7	-4169.4	-864.107

Table 4.6 Availability of different machinery

Month	**Shovel**	**Dumper**	**Front End Loader**
JAN.12	0	0	0
FEB.12	0	0	0
MAR.12	0.561198	0.787202	0
APR-12	0.472747	0.840553	0
MAY-12	0.712033	0.823005	0

JUN-12	0.399244	0.786953	0
JUL-12	0.498624	0.884369	0
AUG-12	0.656674	0.818675	0
SEP-12	0.535511	0.896868	0
OCT-12	0.515425	0.917914	0
NOV-12	0.663885	0.920669	0
DEC-12	0.524543	0.894427	0
JAN-13	0.581964	0.873481	0.9
FEB-13	0.501984	0.748484	0.9
MAR-13	0.369126	0.84215	0.9
FY:12-13	**0.533755**	**0.855182**	**0.9**

CHAPTER-V

Results and Discussion

V.I Production Scheduling

Production scheduling problem is solved for 4736 blocks with a block size of 100x100x20 m^3. Firstly a push back design (Crawford, 1989a) is done for is generated for 5 year. Within the block of push back design long term production scheduling is done with the parameters mentioned in chapter IV and taking constraints and objective function as mentioned in chapter III.

V.I.I Solution Approach

The problem solved using CPLEX software. When the integer programming problem is solved for 5 years with production and grade constraints then a new linear programming file is formed for each specific year to do short term planning. Short term planning is done in order to emphasis on the monthly working which is the required for the operation of mine. CPLEX puts emphasis on the balance optimality and feasibility. Solution details are mentioned below.

Production scheduling for long-term is solved using the equation I to VII specified in chapter III. Solution time for solving the production scheduling problem was 48.14 hours with an NPV value of 4.45938×10^{11} Rs. Short terms production scheduling is done for one year taking the parameters of short term scheduling as mentioned in chapter IV and the NPV value obtained was 7.59796×10^{10} Rs with a solution time of 57.539 minutes. The result of scheduling with different periods is shown in Figure 5.1. Result of constraint value is shown in Table 5.1 and 5.2. Cumulative NPV value is shown in Figure 5.2. Period wise extraction for short term scheduling is shown in Figure 5.3.

Production constraint and grade constraint were satisfied as depicted in Table 5.1 and 5.2 Also, Figure 5.1 shows that slope constraint was satisfied for the long term production schedule. Short term production scheduling also satisfies the constraints taken for the case study. Figure 5.3 shows that slope constraint and reserve was also satisfied for short term production scheduling.

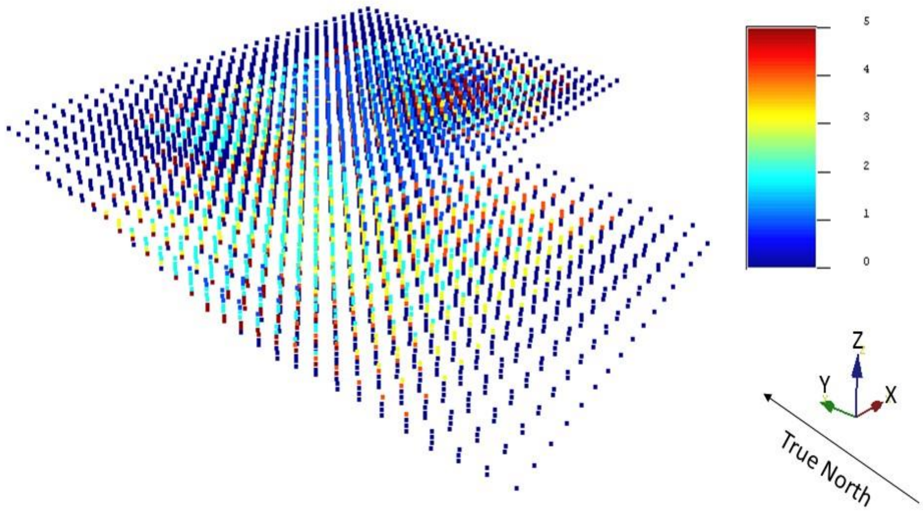

Figure 5.1 Period wise extraction of blocks for long term scheduling

Table 5.1 Result of production scheduling for five year time period for production constraint

Period	Production Target(Min)	Production Target (Max)	Result of scheduling
Year I	48 MT	60 MT	59.856 MT
Year II	48 MT	60 MT	59.16 MT
Year III	48 MT	60 MT	59.392 MT
Year IV	48 MT	60 MT	59.856 MT
Year V	48 MT	60 MT	59.856 MT

Table 5.2 Result of production scheduling for five year time period for grade constraint

Period	Grade Min	Grade Max	Result of scheduling
Year I	3701	5800	4674.849
Year II	3701	5800	4746.053
Year III	3701	5800	5029.903
Year IV	3701	5800	5096.959
Year V	3701	5800	5059.26

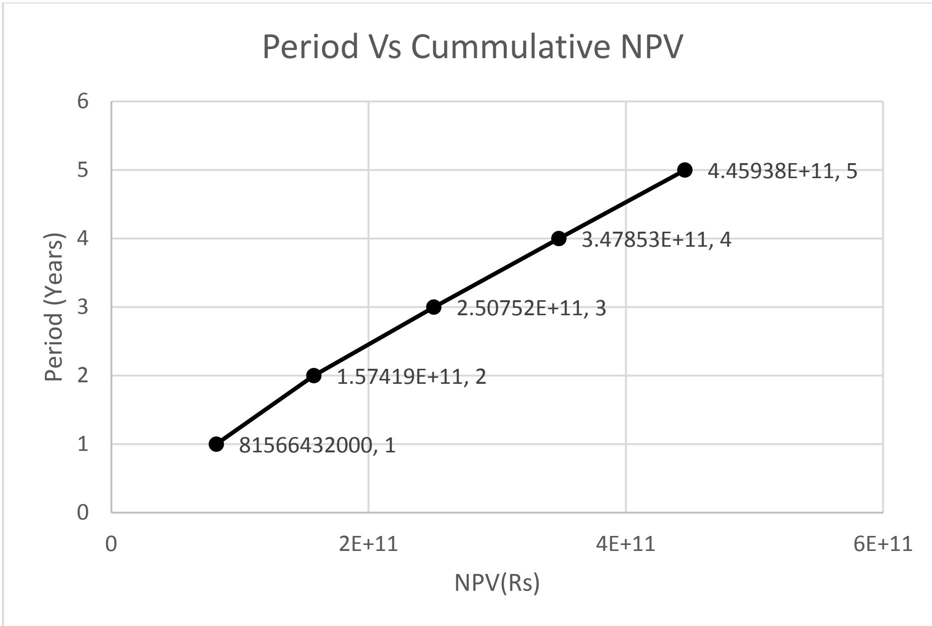

Figure 5.2 Cumulative NPV with period for long term scheduling

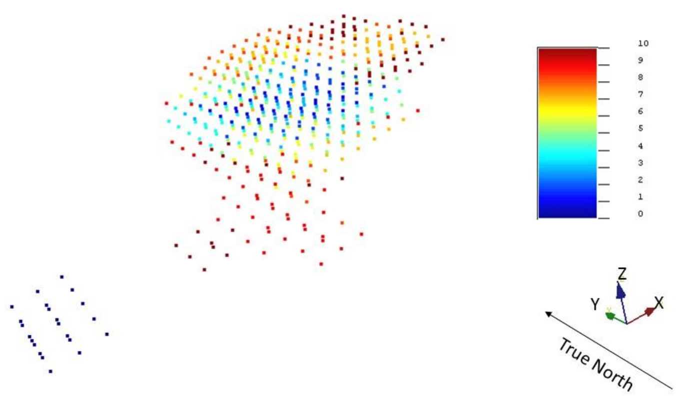

Figure 5.3 Period wise extraction of blocks for short term scheduling

VI.I Mine Fleet Assignment

Mine fleet assignment problem is solved for one short term scheduling period using integer programming.

V.II.I Solution Approach

Fleet assignment problem is solved using Integer Programming Language using CPLEX software. The model of the problem is developed in ILOG Concert Technology using C++ programming. The model is solved using CPLEX environment. C++ program calls the CPLEX software to solve the problem. The results of the mine fleet assignment problem is mentioned below in Table 5.3.

Table 5.3 Result of fleet assignment problem

Entity	**Numbers**
Number of coal dumpers	6
Number of overburden dumpers	9
Number of coal face loaders	2
Number of overburden face loaders	0
Number of coal face shovels	1
Number of overburden face shovels	4

Results of the mine fleet assignment shows that the maximum number of dumpers that can be used are 15. Since the dumpers doesn't work in three shifts, one shift is required for maintenance thus the number of dumpers required to have the desired production be 30 at maximum. Thus a great amount of money can be saved by reducing the numbers of dumpers to 30. Table 5.3 shows that the fleet assignment results satisfies the equipment reserve constraint taken for this case study with number of dumpers 15, shovels 5 and loader 2. Also the production constraint was satisfied with an ore production of 5210 ton/hr. and overburden production of 9124 ton/hr. which is more than the desired production requirement of 4438 ton/hr. and 6873 ton/hr. respectively.

CHAPTER-VI

Conclusion

Block sequencing of an opencast mine is done for long and short term within a nominal time. Integer programming is used for solving production scheduling problem and the results obtained are optimum since branch and cut algorithm gives optimum results in comparison with other algorithms. Solution time for production scheduling problem is also not very high for long term planning and can be solved within 2 days. Schedule for the extraction of blocks, generated in short term planning is used as input parameter for fleet assignment problem and is computationally very fast. Results from the fleet assignment problem indicates that there is a scope for reduction in the size of dumper fleet thus allowing the mining companies to reduce initial investments. Both the formulation of production scheduling and fleet assignment gives and optimal result with all the constraint satisfied.

Production scheduling formulation used this thesis work has one limitation that this approach requires high computational time if solved for larger number of blocks and for large periods. Penalties for over and under production of ore is not incorporated in this formulation. Formulation of the problem is done by solving production scheduling problem and fleet assignment problem one after other, however if both the production scheduling problem and fleet assignment problem is incorporated in one formulation then the result would give the overall profit generated form the extraction of specific block with desired number of fleet requirement. Fleet assignment problem doesn’t include the idle time of dumpers and the time taken for the movement of shovel is not taken in the current formulation. Also in this formulation fleet size of drill machines is not optimized. Drilling and blasting can also be incorporated with this model to generate a model with overall minimum operating cost. Thus there is ample scope for enhancement of this formulation and using both the approaches as one integrated approach.

CHAPTER-VII

References

1. Hochbaum D. S., Chen, A. (2000) Performance analysis and best implementation of old and new algorithms for the open-pit mining problem, Operations Research, 48(6), pp. 894-914.
2. Isaaks H. E., Srivastava M.R. (1990), An introduction to applied geostatistics, Oxford University press.
3. Burt N. C.(2008), An optimization approach to material handling in surface mines, Department of Mathematics and statistics, Curtin University of Technology
4. Sarin, C. S., West-Hansen, J. (2005), The long-term mine production scheduling problem, IEE Transactions 37(2), pp.109-121.
5. Michiotis, A., Xerocostas, D., Galitis, N. (1998), A new integrated system for selecting mining equipment, Computers & Industrial Engineering. 34(2), pp. 391 – 397.
6. Elbrond, J., Soumis, F. (1987), Towards integrated production planning and truck dispatching in open pit mines, International Journal of Surface Mining, 1, pp. 1-6.
7. Luenberger, D. (2003), Linear and Nonlinear Programming, 2nd edn, Kluwer Academic, Boston.
8. Hustrulid W. and Kuchta K, editors. Open Pit Mine Planning and Design. Taylor and Francis, London, UK, 2006.
9. Barbaro,R.,W. and Ramani, R.,V., Generalized multi-period MIP model for production scheduling and processing facilities selection and location, Mining Engineering 38(2) (1986), pp.107–114.
10. Mukherjee, K., Application of an interactive method for MOILP in project selection decision – A case from Indian coal mining industry, International Journal of Production Economics 36 (1994), pp.203–211.
11. Caccetta, L. & Hill, S. (2003), `An application of branch and cut to open pit mine Scheduling', Journal of Global Optimization 27, 349-365.
12. Bley, A., Boland, N., Fricke, C., Froyland, G., 2010. A strengthened formulation and cutting planes for the open pit mine production scheduling problem. Computers & Operations Research 37 (9), 1641–1647.

13. Padberg, M. and Rinaldi, G., (1991), A Branch-and-Cut Algorithm for the Resolution of Large-Scale Symmetric Traveling Salesman Problems. Siam Review: 60–100.
14. Ramazan, S., 2007. The new fundamental tree algorithm for production scheduling of open pit mines. European Journal of Operational Research 177, 1153–1166.
15. Gershon, M., 1987. Heuristic approaches for mine planning and production scheduling. International Journal of Mining and Geological Engineering 5 (1), 1–13.
16. Tolwinski, B., Underwood, R., 1996. A scheduling algorithm for open pit mines. IMA Journal of Mathematics Applied in Business & Industry 7, 247–270.
17. Denby, B., Schofield, D., 1994. Open-pit design and scheduling by use of genetic algorithms. Transactions of the Institution of Mining and Metallurgy 103, A21– A26.
18. Ferland, J.A., Amaya, J., Djuimo, M.S., 2007. Application of a particle swarm algorithm to the capacitated open pit mining problem. In: Mukhopadhyay, S., Sen Gupta, G. (Eds.), Autonomous Robots and Agents. Springer-Verlag, pp. 127– 133.
19. Newman, A.M., Rubio, E., Caro, R., Weintraub, A., Eurek, K., 2010. A review of operations research in mine planning. Interfaces 40 (3), 222–245.
20. Souza, M.J.F., Coelho, I.M., Ribas, S., Santos, H.G., Merschmann, L.H.C., 2010. A hybrid heuristic algorithm for the open-pit-mining operational planning problem. European Journal of Operational Research 207, 1041–1051.
21. Topal, E., Ramazan, S., 2010. A new MIP model for mine equipment scheduling by minimizing maintenance cost. European Journal of Operational Research 207, 1065–1071.
22. Ravenscroft, P.J., 1992. Risk analysis for mine scheduling by conditional simulation. Transactions of the Institution of Mining and Metallurgy, Section A: Mining Technology, A104–A108.
23. Dowd, P.A., 1994. Risk assessment in reserve estimation and open-pit planning. Transactions of the Institution of Mining and Metallurgy 103, A148–A154.
24. Dimitrakopoulos, R., Farrelly, C.T., Godoy, M., 2002. Moving forward from traditional optimization: grade uncertainty and risk effects in open pit mine design. IMM Transactions 111, A82–A88.
25. Godoy, M., Dimitrakopoulos, R., 2004. Managing risk and waste mining in long-term production scheduling of open-pit mines. SME Transactions 316, 43–50.

26. Eldin, N. & Mayfield, J. (2005), `Determination of most economical scrapers fleet', Journal of Construction Engineering and Management pp. 1109-1114.
27. Smith, S. D., Wood, G. S. & Gould, M. (2000), `A new earthworks estimating methodology', Construction Management and Economics 18(2), 219-228.
28. Morgan, W. C. & Peterson, L. L. (1968), `Determining shovel-truck productivity', Mining Engineering pp. 76-80.
29. Burt, C. N. & Caccetta, L. (2007), `Match factor for heterogeneous truck and loader fleets', International journal of mining, reclamation and environment 21, 262-270.
30. Webster, D. & Reed, R. (1971), `A material handling system selection model', AIIE Transactions 3(1), 13-20.
31. Blackwell, G. H. (1999), `Estimation of large open pit haulage truck requirements', CIM Bulletin 92(1028), 143-148.
32. O'Shea, J. B. (1964), An application of the theory of queues to the forecasting of shovel truck fleet productions, Master's thesis, University of Illinois, Urbana, Illinois.
33. Farid, F. & Koning, T. L. (1994), `Simulation verifies queuing program for selecting loader-truck fleets', Journal of Construction Engineering and Management 120(2), 386-404.
34. Jayawardane, A. & Harris, F. (1990), `Further development of integer programming in earthwork optimization', Journal of Construction Engineering and Management 116(1), 18-34.
35. Dagdelen, K., Topal, E. & Kuchta, M. (2000), Linear programming model applied to scheduling of iron ore production at the Kiruna mine, Sweden, in Panagiotou & Michalakopoulos (2000), pp. 187-192.
36. Dagdelen, K. & Asad, M. W. (2002), Optimum cement quarry scheduling algorithm, in Bandopadhyay (2002), pp. 697-709.
37. Johnson, T. B., Dagdelen, K. & Ramazan, S. (2002), Open pit mine scheduling based on fundamental tree algorithm, in Bandopadhyay (2002), pp. 147-159.
38. Kumral, M. & Dowd, P. (2005), `A simulated annealing approach to mine production scheduling', Journal of the Operational Research Society 56, 922-930.
39. Er_celebi, S. & Kirmanli_, C. (2000), Review of surface mining equipment selection techniques, in Panagiotou & Michalakopoulos (2000), pp. 547-553.

40. Celebi, N. (1998), `An equipment selection and cost analysis system for open pit coal mines', International Journal of Surface Mining, Reclamation and Environment 12, 181-187.
41. Morgan, B. (1994b), Optimizing truck-loader matching, in Pasamehmetoglu (1994), pp. 313-320.
42. Cebesoy, T., Gzen, M. & Yah_si, S. (1995), A systematic decision making model for optimum surface mining equipment selection, in Singhal, Mehrotra, Hadjigeorgiou & Poulin (1995), pp. 369-377.
43. Cohen R., Katzir L., Raz D.,(2006) An efficient approximation for the generalized assignment problem. Information Processing Letter, Elsevier,Volume 100, Issue 4, pp 162-166.
44. Hall, B. E. (2000), Simulation modelling of mining systems, in `Proceedings of MassMin 2000', The Australiasian Institute of Mining and Metallurgy, The Australiasian Institute of Mining and Metallurgy, Melbourne, pp. 83-95.
45. Shi, J. J. (1999), `A neural network based system for predicting earthmoving production', Construction Management and Economics 17, 463-471.
46. Schexnayder, C., Knutson, K. & Fente, J. (2005), `Describing a beta probability distribution function for construction simulation', Journal of Construction Engineering and Management 131(2), 221-229.
47. Frimpong, S., Asa, E. & Szymanski, J. (2002), `Intelligent modeling: Advances in open pit mine design and optimization research', International Journal of Surface Mining, Reclamation and Environment 16(2), 134-143.
48. Bandopadhyay, S. & Venkatasubramanian, P. (1987), `Expert system as decision aid in surface mine equipment selection', International Journal of Surface Mining 1, 159-165.
49. Haidar, A. & Naoum, S. (1995), Selection of opencase mine equipment using knowledge base and genetic algorithms, in Singhal et al. (1995), pp. 409-414.
50. Ganguli, R. & Bandopadhyay, S. (2002), `Expert system for equipment selection', International Journal of Surface Mining, Reclamation and Environment 16(3), 163-170.
51. Naoum, S. & Haidar, A. (2000), `A hybrid knowledge base system and genetic algorithms for equipment selection', Engineering, Construction and Architectural Management 7(1), 3-14.

52. Marzouk, M. & Moselhi, O. (2004), `Multiobjective optimization of earthmoving operations', Journal of Construction Engineering and Management 20(6), 535-543.
53. Crawford, J.T 1989a, Pushback design steps, Personal Communication.