

Optimizing block extraction sequence with MIP method and investigating the effect of road condition on truck cycle time

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Abstract

Mine long-term plans define the complex strategy of displacement of ore, waste, overburden, and tailings over the mine life. The objectives of long-term mine plans are to manage and maximize the future cash flows and to minimize the environmental footprint of mining operations. Among the operation tasks, the haulage is the most expensive operation. We have used a mixed integer programming formulation to schedule the order of extraction of a mining bench in an iron ore mine. The objective function was to maximize the net present value of the operation, while meeting the qualitative and quantitative production constraints. Also, we have used simulation to investigate the affect of road conditions on truck cycle time.

1. Introduction

The operation tasks in open-pit mines consist of drilling, blasting, loading, haulage and general services. Among them, the haulage is the most expensive operation that occupies more than 50% of the total operation cost in open-pit mines. Therefore, minimizing the haulage cost can be one of the most critical factors in ore production. The shovel-truck haulage system is common in open-pit mines due to the flexibility of the fleet. The haulage cost of shovel-truck system is dependent on the productivity of an operating truck which can be represented by the average truck cycle time.

1.1. Introduction to linear programming (LP) and integer programming (IP)

A major element of mine planning is the optimization of long-term production schedule. The aim is to maximize the overall discounted net revenue from a mine within operational constraints such as mining slope, grade blending, ore production and mining capacity. Integer programming (IP) and linear programming (LP) mathematical models are considered to be powerful tools in optimizing mine schedules, and there have been major efforts in applying them to mining projects (Ramazan *et al.*, 2004).

Linear programming (LP): Linear programming uses a mathematical model to describe the problem of concern. The adjective linear means that all the mathematical functions in this model are required to be linear functions. Linear programming involves the planning of activities to obtain an optimal result, a result that reaches the specified goal best (according to the mathematical model) among all feasible alternatives (Hillier, 2005).

Integer programming (IP): In many practical problems, the decision variables actually make sense only if they have integer values. If requiring integer values is the only way in

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which a problem deviates from a linear programming formulation, then it is an integer programming (IP) problem. The mathematical model for integer programming is the linear programming model with the one additional restriction that the variables must have integer values. If only some of the variables are required to have integer values (so the divisibility assumption holds for the rest), this model is referred to as mixed integer programming (MIP). With just two choices, we can represent such decisions by decision variables that are restricted to just two values, say 0 and 1. Thus, the j^{th} yes-or-no decision would be represented by, say, x_j such that

$$x_j = \begin{cases} 1 & \text{If decision } j \text{ is yes.} \\ 0 & \text{If decision } j \text{ is no.} \end{cases}$$

Such variables are called binary variables (or 0–1 variables). Consequently, IP problems that contain only binary variables sometimes are called binary integer programming (BIP) problems (or 0–1 integer programming problems) (Hillier, 2005).

2. An abstract description of open pit mining

Ore bodies in open pit mines are represented by block models (figure 1). A block model divides ore and waste blocks adjacent to each other. The model may have several hundred thousand blocks depending on the size of the orebody and the size of the blocks. The size of the blocks is a function of the equipment used and the blasting pattern practiced. The average ore content of each block is calculated using geostatistical methods.

Open pit mining is a mineral extraction method by which the ore body is accessed by opening a large stretch of ground to expose the ore to air. Mining begins with a small pit in the surface, and then proceeds to a larger pit, which encloses the small pit, and the process continues until a final pit is reached (figure2). A mining sequence is obtained from a series of nested pits (figure3).

The time it will take to mine all the pits in the sequence will define the mine life, and the boundaries of the last pit in the sequence will determine the ultimate pit limits.

The blocks with average grade less than the cutoff grade are considered as waste blocks, and sometimes it is necessary to mine them in order to reach the ore blocks. The material mined from waste blocks is sent to the waste dump. On the other hand, some ore blocks may have to be left without mining because too many waste blocks must be mined to reach those blocks.

As seen in figure 3, mining in open pits starts from top and proceeds towards the bottom. Pit 1 is mined first, and subsequently Pit 2 is reached by mining the incremental blocks between Pit 1 and 2. In mining engineering terminology, it is said that Pit 2 is reached by a pushback from Pit 1. The most essential problem in long-term production planning is the determination of the set of pushbacks, that is, the mining sequence, to maximize the net present value (NPV) of the project. The results of the long term production planning are used as guides for the short- term production planning which may be for a quarter, a month or a week.

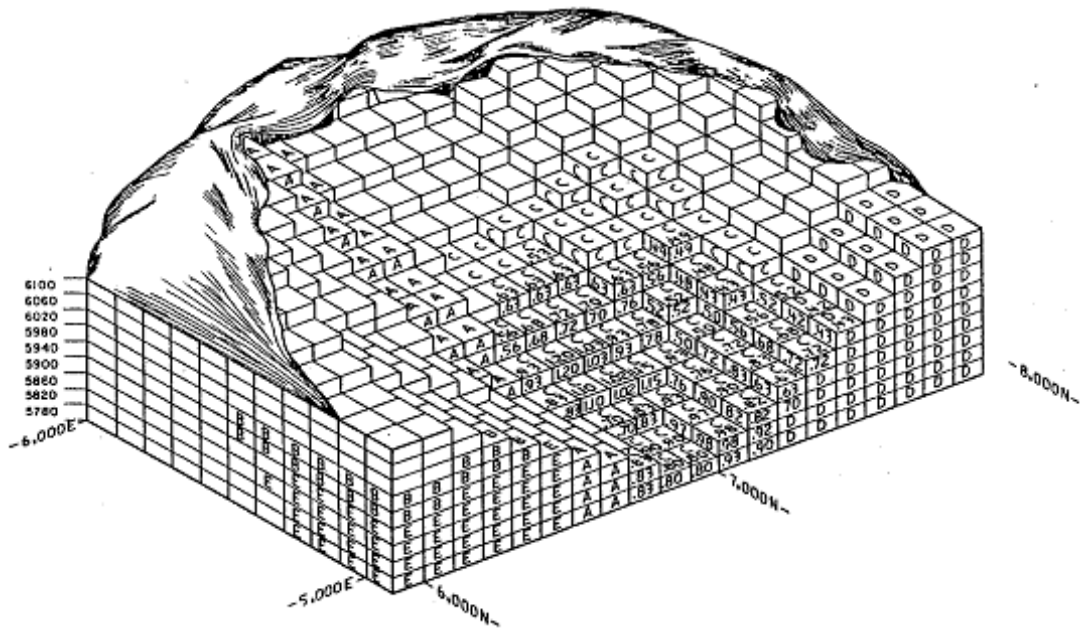


Fig 1. Diagrammatic view of a 3-D block matrix containing can orebody (Hustrulid *et al.*, 2006)



Fig 2. Sungun copper mine pit, Iran

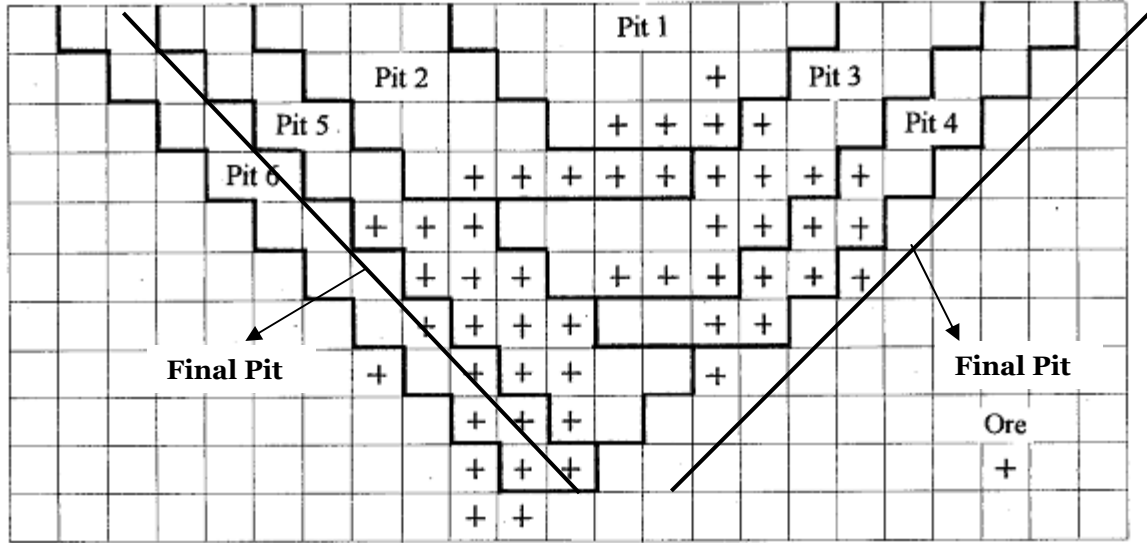


Fig 3. Two- dimensional view of nested pits and final pits
 (Pits 1 to 6 are nested pits) (Sevim *et al.*, 1998)

3. MIP formulation for multi-period long-term production scheduling model

MIP models are generally used to maximize the overall discounted economic value, or net present value (NPV), of a mining project. Equation (1) was used as the objective function.

$$\text{Maximize } \sum_{t=1}^T \sum_{n=1}^N \frac{BEV_n^t}{(1+i)^t} \times X_n^t = \text{Minimize} [-\sum_{t=1}^T \sum_{n=1}^N \frac{BEV_n^t}{(1+i)^t} \times X_n^t] \quad (1)$$

Where T is the maximum number of scheduling periods, N is the total number of blocks to be scheduled, BEV_n^t is block economic value of block n in period t, i is interest rate and X_n^t is a binary variable, equal to 1 if the block n is to be mined in period t, otherwise 0.

3.1. Grade blending constraints

The average grade of the material sent to the mill has to be less than or equal to a certain grade value, G_{max} , for each period, t (Ramazan *et al.*, 2004).

$$\sum_{n=1}^N (g_n - G_{max}) \times Ot_n \times X_n^t \leq 0 \quad (2)$$

Where g_n is the average grade of block n, and Ot_n is the ore tonnage in block n.

The average grade of the material sent to the mill has to be greater than or equal to a certain grade value, G_{min} , for each period, t.

$$\sum_{n=1}^N (g_n - G_{\min}) \times Ot_n \times X_n^t \geq 0 \quad (3)$$

3.2. Reserve constraints

Reserve constraints are constructed for each of the blocks to state that all the blocks in the model considered have to be mined once (Ramazan *et al.*, 2004).

$$\sum_{t=1}^T X_n^t = 1 \quad (4)$$

3.3. Processing capacity constraints

The total tonnage of ore processed cannot be more than the processing capacity (PC_{\max}) in any period, t (Ramazan *et al.*, 2004).

$$\sum_{n=1}^N (Ot_n \times X_n^t) \leq PC_{\max} \quad (5)$$

The total tonnage of ore processed cannot be less than a certain amount (PC_{\min}) in any period, t.

$$\sum_{n=1}^N (Ot_n \times X_n^t) \geq PC_{\min} \quad (6)$$

3.4. Mining capacity

The total amount of material (waste and ore) to be mined cannot be more than the total available equipment capacity (MC_{\max}) for each period, t (Ramazan *et al.*, 2004).

$$\sum_{n=1}^N (Ot_n + W_n) \times X_n^t \leq MC_{\max} \quad (7)$$

Where W_n is the tonnage of waste material in block n .

To force the MIP model to produce balanced waste production throughout the periods, a lower bound (MC_{\min}) may need to be implemented as follows:

$$\sum_{n=1}^N (O_{t_n} + W_n) \times X_n^t \geq MC_{\min} \quad (8)$$

The number of binary variables required for the MIP model is equal to the number of blocks multiplied by the total periods to be scheduled, as can be seen in the formulations above.

4. Illustration of an example

In this section, a scheduling optimization example with 415 blocks has been explained. All necessary steps for problem setting have been explained in detail.

The goal is extraction of all 415 blocks in five periods while maximizing the net present value as represented by equation (1).

Step 1. Analysis of blocks information

Block model is created with GEMS6.1 and Whittle4.1 software. For this suppose the drill- holes data are used as input of Gems then the block model is created. After that, information is saved in Matlab file format.

These 415 blocks are a segment of an orebody block model of a real iron ore deposit. Information of each block is as follows:

1x415 struct array with fields:

XI, YI, ZI:	Index of each block in the block model
X,Y, Z:	Coordinates of the block
MCAF:	Mining cost adjustment factor
PCAF:	Processing cost adjustment factor
gradeS, gradeP, gradeMWT:	Grade of Sulphur, Phosphor and Fe
OreTonnes:	Total tonnage of ore in the block
WasteTonnes :	Total tonnage of waste in the block
OreValue:	Value of ore in the block
WasteCosts:	Costs of waste in the block
BlockTonnage:	Total tonnage of the block(waste + ore)
EBV:	Economic block value
P, S, MWT:	Tonnage of Phosphor, Sulphur and Fe in the block

All blocks were analyzed and necessary graphs and statistic analysis carried out using Matlab. Figure 4 shows grade distribution histogram. According to this histogram, maximum value of grade (G_{max}) is equal to 0.8 percent.

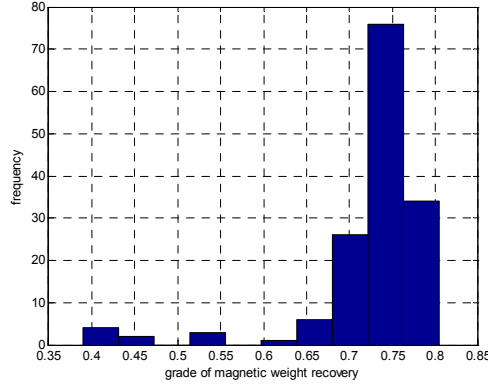


Fig 4. Grade histogram for ore blocks

Step 2. Setting up the problem for solving with Matlab

The Matlab **bintprog** function solves binary integer programming problems of the form:

$$\text{Minimize } f'.x \quad \text{such that} \quad \begin{aligned} Ax &\leq b \\ Aeq.x &= beq \end{aligned}$$

Where f, b, and beq are vectors, A and Aeq are matrices, and the solution x is required to be a binary integer vector—that is, its values can only take on the values 0 or 1.

To solve this problem in Matlab we have to use following function:

$$x = \text{bintprog}(f,A,b, Aeq,beq)$$

To set the problem in format of Matlab bintprog function the following steps have to be followed:

Step 3. Creating matrix f

The function that we want to maximize with interest rate equal 15% is as follows:

$$\sum_{t=1}^T \sum_{n=1}^N \frac{BEV_n^t}{(1+i)^t} \times X_n^t \Rightarrow \sum_{t=1}^5 \sum_{n=1}^{415} \frac{BEV_n^t}{(1+i)^t} \times X_n^t$$

The expanded formats of function for each period are as follows:

$$\text{Function for the first period: } \left(\frac{BEV_1^1}{(1+0.15)^1} x_1^1 + \frac{BEV_2^1}{(1+0.15)^1} x_2^1 + \dots + \frac{BEV_{415}^1}{(1+0.15)^1} x_{415}^1 \right)$$

$$\text{Function for the second period: } \left(\frac{BEV_1^2}{(1+0.15)^2} x_1^2 + \frac{BEV_2^2}{(1+0.15)^2} x_2^2 + \dots + \frac{BEV_{415}^2}{(1+0.15)^2} x_{415}^2 \right)$$

$$\text{Function for the third period: } \left(\frac{BEV_1^3}{(1+0.15)^3} x_1^3 + \frac{BEV_2^3}{(1+0.15)^3} x_2^3 + \dots + \frac{BEV_{415}^3}{(1+0.15)^3} x_{415}^3 \right)$$

$$\text{Function for the fourth period: } \left(\frac{BEV_1^4}{(1+0.15)^4} x_1^4 + \frac{BEV_2^4}{(1+0.15)^4} x_2^4 + \dots + \frac{BEV_{415}^4}{(1+0.15)^4} x_{415}^4 \right)$$

$$\text{Function for the fifth period: } \left(\frac{BEV_1^5}{(1+0.15)^5} x_1^5 + \frac{BEV_2^5}{(1+0.15)^5} x_2^5 + \dots + \frac{BEV_{415}^5}{(1+0.15)^5} x_{415}^5 \right)$$

In this case, we want to maximize the objective function; therefore, we have to multiply the function by a negative sign.

Where, f is a column matrix with N×T elements that N is number of blocks and T is number of periods.

$$f = \left[-\frac{BEV_1^1}{(1.15)^1} \quad \dots \quad -\frac{BEV_{415}^1}{(1.15)^1} \quad -\frac{BEV_1^2}{(1.15)^2} \quad \dots \quad -\frac{BEV_{415}^2}{(1.15)^2} \quad \dots \quad -\frac{BEV_{415}^5}{(1.15)^5} \right]^T$$

Step 4. Creating [A], {x}, {b}, [Aeq] and {beq}

4.1. Creating coefficients matrix of the linear inequality constraints [A]

We want to maximize f subject to $[A].\{x\} \leq \{b\}$, where [] represents a matrix and { } represents a vector. A is the matrix containing the coefficients of the linear inequality constraints, b is the vector corresponding to the right-hand side of the linear inequality constraints and x is solution.

Matrix A has m rows and n columns that m and n given by $m=NC \times T$ and $n=N \times T$. Where, NC is number of inequality constraints, T is number of periods that blocks are extracted in and N is number of blocks.

Matrix A is created by following inequality constraint equations:

$$\text{Constraint 1(A1): } \sum_{n=1}^N (g_n - G_{\max}) \times Ot_n \times X_n^t \leq 0$$

$$\text{Constraint 2(A2): } \sum_{n=1}^N (g_n - G_{\min}) \times Ot_n \times X_n^t \geq 0$$

$$\text{Constraint 3(A3): } \sum_{n=1}^N (Ot_n \times X_n^t) \leq PC_{\max}$$

$$\text{Constraint 4(A4): } \sum_{n=1}^N (Ot_n \times X_n^t) \geq PC_{\min}$$

$$\text{Constraint 5(A5): } \sum_{n=1}^N (Ot_n + W_n) \times X_n^t \leq MC_{\max}$$

$$\text{Constraint 6(A6): } \sum_{n=1}^N (Ot_n + W_n) \times X_n^t \geq MC_{\min}$$

Since, constraints must be written in $[A].\{x\} \leq \{b\}$ form, conditions 2, 4, and 6 are written as follows:

$$\sum_{n=1}^N (G_{\min} - g_n) \times Ot_n \times X_n^t \leq 0$$

$$\sum_{n=1}^N -(Ot_n \times X_n^t) \leq -PC_{\min}$$

$$\sum_{n=1}^N -(Ot_n + W_n) \times X_n^t \leq -MC_{\min}$$

Table 1 shows summary of inequality constraints and short description about them.

Table 1. constructing matrix A

$(g_n - G_{\max}) \times Ot_n$	This constraint is exerted from first row to T th row. First, value of this equation is calculated for each block, and then, they are replaced in row one period 1, row 2 period 2 and so to T th row.
$(G_{\min} - g_n) \times Ot_n$	This constraint is exerted from (T+1) th row to (2T) th row. Value of this equation is calculated for each block, and then, is replaced in row (T+1) period 1, row (T+2) period 2 and so to (2T) th row.
Ot_n	Ore tonnage of each block is replaced from (2T+1) th row to (3T) th row into the related period.
$-Ot_n$	Ore tonnage of each block is multiplied by (-1) and then is replaced from (3T+1) th row to (4T) th row into the related period.
$(Ot_n + W_n)$	Total tonnage of each block (ore+waste) is replaced from (4T+1) th row to (5T) th row into the related period.
$-(Ot_n + W_n)$	Total tonnage of each block (ore+waste) is multiplied by (-1) and then is replaced from (5T+1) th row to (6T) th row into the related period.

When the values of equation are replaced in related period of each row, other elements in those rows have to be zero. Figure 5 shows how matrix A is created. AC_n indicates value of constraint C for block n. For instance, A1₁ is the value of constraint 1 for block 1 and A2₄₁₁ is the value of constraint 2 for block 411. The first number is number of constraints and second one number of blocks.

4.1.1 Creating vector x

Vector x with elements $x_j \{j = 1, 2, 3, \dots, 2075\}$ is the solution of the problem. This vector has $(T \times N)$ elements. The following relationship governs among elements of vector x .

$$\left. \begin{array}{l}
 \text{Period 1 : } x_1, x_2, \dots, x_N \\
 \text{Period 2 : } x_{N+1}, x_{N+2}, \dots, x_{2N} \\
 \text{Period 3 : } x_{2N+1}, x_{2N+2}, \dots, x_{3N} \\
 \cdot \\
 \cdot \\
 \cdot \\
 \text{Period T : } x_{[(T-1) \times N] + 1}, x_{[(T-1) \times N] + 2}, \dots, x_{T \times N}
 \end{array} \right\} \begin{array}{l}
 x_1 = x_{N+1} = \dots = x_{[(T-1) \times N] + 1} \\
 x_2 = x_{N+2} = \dots = x_{[(T-1) \times N] + 2} \\
 \cdot \\
 \cdot \\
 \cdot \\
 x_N = x_{2N} = \dots = x_{TN}
 \end{array}$$

Period 1 1 - 415					Period 2 416 - 830					Period 3 831 - 1245					Period 4 1246 - 1660					Period 5 1661 - 2075				
$A1_1$	.	.	.	$A1_{415}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	$A1_1$	.	.	.	$A1_{415}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	$A1_1$	.	.	.	$A1_{415}$	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$A1_1$	.	.	.	$A1_{415}$	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$A1_1$	.	.	.	$A1_{415}$
$A2_1$	.	.	.	$A2_{415}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	$A2_1$	.	.	.	$A2_{415}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	$A2_1$	.	.	.	$A2_{415}$	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$A2_1$	.	.	.	$A2_{415}$	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$A2_1$	.	.	.	$A2_{415}$
.
.
.
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$A6_1$	.	.	.	$A6_{415}$

Dimension of matrix $A = (NC \times T) \times (N \times T) = (6 \times 5) \times (415 \times 5) = 30 \times 2075$

Fig 5. Method of coefficient matrix creation

4.1.2 Creating vector **b**

b is a vector containing the constants of the linear inequality constraints. Dimension of this vector depends on dimensions of matrix **A** and vector **x**.

$$[A]_{(NC \times T) \times (N \times T)} \cdot \{x\}_{(N \times T) \times 1} = \{b\}_{(NC \times T) \times 1}$$

In this case dimension of **b** is equal to 30×1.

4.1.3 Coefficients matrix of the linear equality constraints [**Aeq**] and vector{**beq**}

In addition to linear inequality constraints, there are some equality constraints that we cannot replace them into the matrix **A**. In this case, we know each block can be mined once during the mine life.

Condition 7(A7): $\sum_{t=1}^T X_n^t = 1$

$$x_1 + x_{N+1} + \dots + x_{[(T-1) \times N] + 1} = 1$$

$$x_2 + x_{N+2} + \dots + x_{[(T-1) \times N] + 2} = 1$$

.

$$x_N + x_{2N} + \dots + x_{TN} = 1$$

To create matrix **Aeq** the related coefficient of each block have to be replaced by 1. Matrix **Aeq** is a $N \times (T \times N)$ matrix. **beq** is the vector corresponding to the right-hand side of the linear equality constraints and **x** is solution.

In this case at the following matrix the first row indicates the coefficients of block number 1 during the scheduling periods (five periods). $x_1, x_{416}, x_{831}, x_{1246}$ and x_{1661} are solution of problem for block number 1. If $x_1=1$ thus block 1 is extracted in period 1 and $x_{416}=x_{831}=x_{1246}=x_{1661}=0$, if $x_{416}=1$ thus block 1 is extracted in period 2 and $x_1=x_{831}=x_{1246}=x_{1661}=0$, and etc. Figure 6 shows how matrix **Aeq** is created. Therefore, the following condition must be governed because each block can be mined once. For instance, for block number one we can write:

$$1 \times x_1 + 1 \times x_{416} + 1 \times x_{831} + 1 \times x_{1246} + 1 \times x_{1661} = 1$$

After creating all necessary matrices and vector this problem was solved using Matlab and Tomlab toolbox and the answer was as follows:

bintprog (CPLEX): bintprog converged to a solution X.

Table 2 shows the summary of important information for each period. Tonnages of ore and waste that are extracted in each period are shown in figure 7.

Figures 8 and figure 9 show the average grade and value of function for each period, respectively.

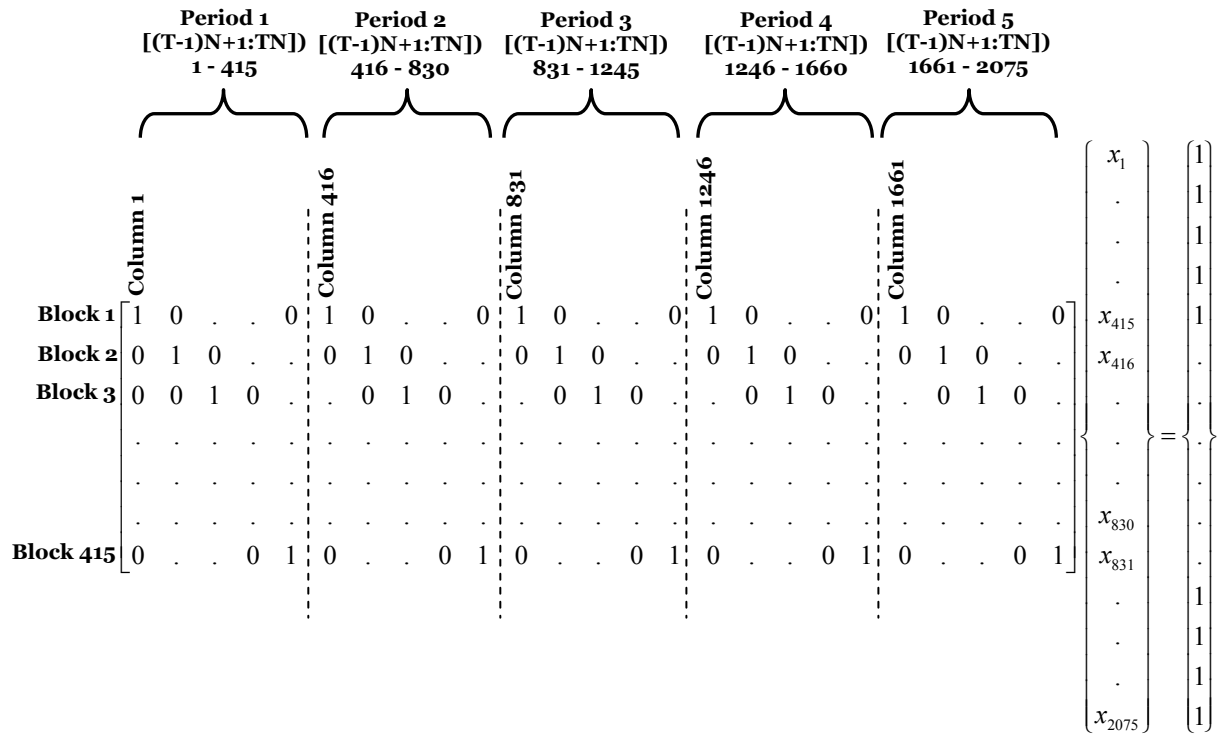


Fig 6. Method of Aeq matrix creation

Table 2. Summary of obtained answers for each period.

	Period 1	Period 2	Period 3	Period 4	Period 5
Waste (t)	1660332	2484400	2498464	2501276	3750976
Ore (t)	2496000	2496000	2496000	2496000	1244066
Waste+Ore (t)	4156332	4980400	4994464	4997276	4995042
$f = \sum \frac{BEV_n}{(1+i)^t}$	1.4325×10^8	1.2010×10^8	1.0121×10^8	0.8538×10^8	0.2673×10^8
$\sum_{t=1}^5 \sum_{n=1}^{415} \frac{BEV_n^t}{(1+i)^t}$	4.7668×10^8				

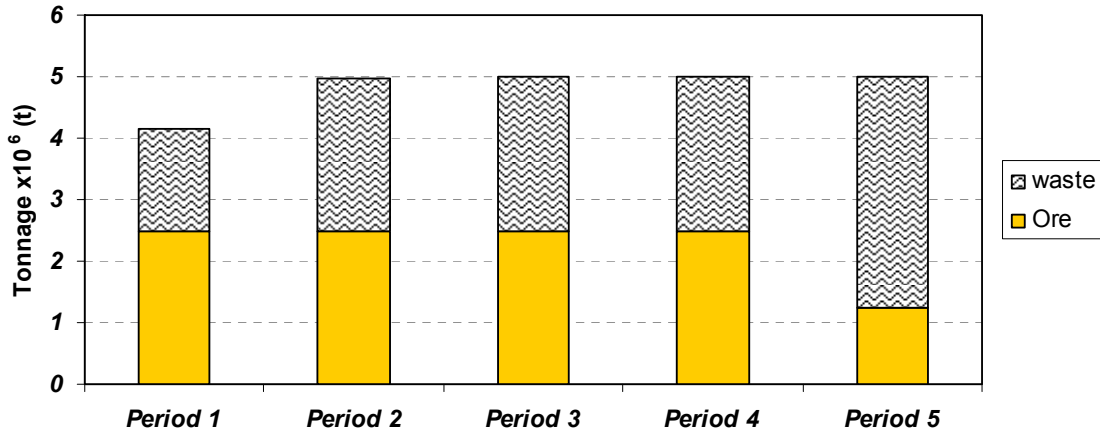


Fig 7. Amount of ore and waste in each period

To calculate average grade of each period equation (9) was used:

$$g_{ave}^t = \frac{\sum (g_n^t \times O_n^t)}{\sum O_n^t} \tag{9}$$

Where, g_{ave}^t is average grade of period t, g_n^t grade of block number n that is extracted in period t and O_n^t ore tonnage of block number n that is extracted in period t.

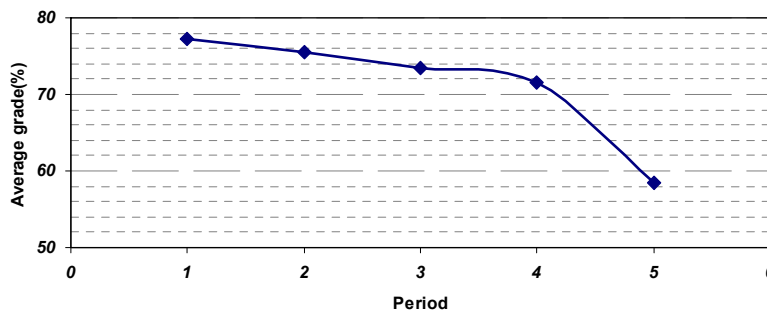


Fig 8. Average grade of Fe% in each period

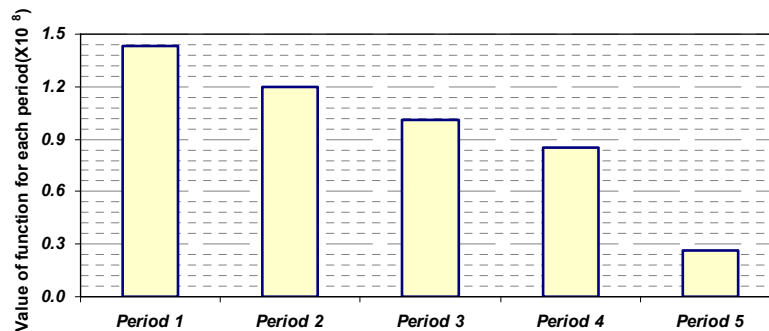


Fig 9. Annual discounted cash flows

5. Problem definition of the transportation problem

Figure 10 shows plan view of the working bench and roads that have been used for simulation. Distance between working bench as starting point and destinations are divided into two parts. The first part is from each block to the starting point of main road and the second part is from the starting point of main road to destinations. The main road is 7 km and the coordinates of the starting point of the main road are $x=96000$, $y=600740$. Distance between each block and destination is given by:

$$D(m) = 7000 + d_{B-S} \quad (10)$$

Where, D is the total distance and d_{B-S} is the distance between each block and the main road starting point.

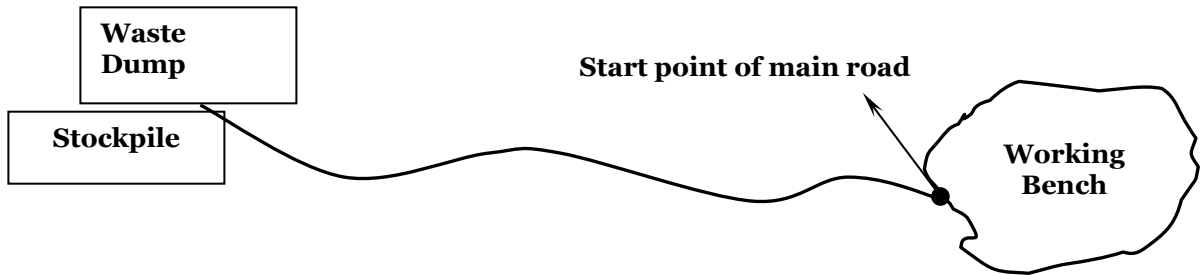


Fig 10. Plan view of working area

6. Simulation of transportation system with Simulink

Average truck cycle time is given by equation (11)

$$T_{Truck} = ST_{loading} + L_t + T_{t-fill} + ST_{unloading} + T_{unloading} + T_{t-empty} + AD_t \quad (11)$$

Where, T_{Truck} is the truck cycle time, $ST_{loading}$ is the spot time at loading, L_t is the loading time, T_{t-fill} is the travel time to dump or stockpile (fill), $ST_{unloading}$ is the spot time at unloading, $T_{unloading}$ is the unloading time, $T_{t-empty}$ is the travel time moving to working bench (empty) and AD_t is the average delay time including both waits and delays.

To estimate loading time we can use equation (12) :

$$L_t = \frac{t_{capacity} \times SH_{t-cyc}}{SH_{capacity}} \quad (12)$$

Where, L_t is the loading time of truck, $t_{capacity}$ is the truck capacity, SH_{t-cyc} is the shovel cycle time and $SH_{capacity}$ is the shovel capacity.

In this case, we can use equations (13) and (14) as constitutive relationships for the main road:

$$T_{t-fill} = \frac{x}{V_{t-fill}} \quad (13)$$

$$T_{t-empty} = \frac{x}{V_{t-empty}} \quad (14)$$

Where, x is the distance, V_{t-fill} is the velocity of truck after loading and $V_{t-empty}$ is the velocity of truck after unloading. The assumption is that in the working area the velocity of truck because of extraction is 85% less than velocity on the main road, therefore equations (13) and (14) can be rewritten as follows:

$$T_{t-fill} = \frac{x}{V_{t-fill}} + \frac{x_w}{0.15 \times V_{t-fill}} = \frac{0.15x + x_w}{0.15 \times V_{t-fill}}$$

$$T_{t-empty} = \frac{x}{V_{t-empty}} + \frac{x_w}{0.15 \times V_{t-empty}} = \frac{0.15x + x_w}{0.15 \times V_{t-empty}}$$

$$\begin{aligned} T_{t-fill} + T_{t-empty} &= \frac{0.15x + x_w}{0.15 \times V_{t-fill}} + \frac{0.15x + x_w}{0.15 \times V_{t-empty}} = \frac{V_{t-empty}(0.15x + x_w) + V_{t-fill}(0.15x + x_w)}{0.15 \times V_{t-fill} \times V_{t-empty}} \\ &= \frac{(V_{t-empty} + V_{t-fill})(0.15x + x_w)}{0.15 \times V_{t-fill} \times V_{t-empty}} \end{aligned}$$

Where, x_w is the distance between each block and starting point of main road. Using the constitutive relationships we can rewrite equation (11) as follows:

$$T_{Truck} = ST_{loading} + \frac{t_{capacity} \times SH_{t-cyc}}{SH_{capacity}} + \frac{(V_{t-empty} + V_{t-fill})(0.15x + x_w)}{0.15 \times V_{t-fill} \times V_{t-empty}} + ST_{unloading} + T_{unloading} + AD_t$$

A Simulink simulation model was built to capture the truck travel cycle time based on the above equation. Figure 11 shows the model.

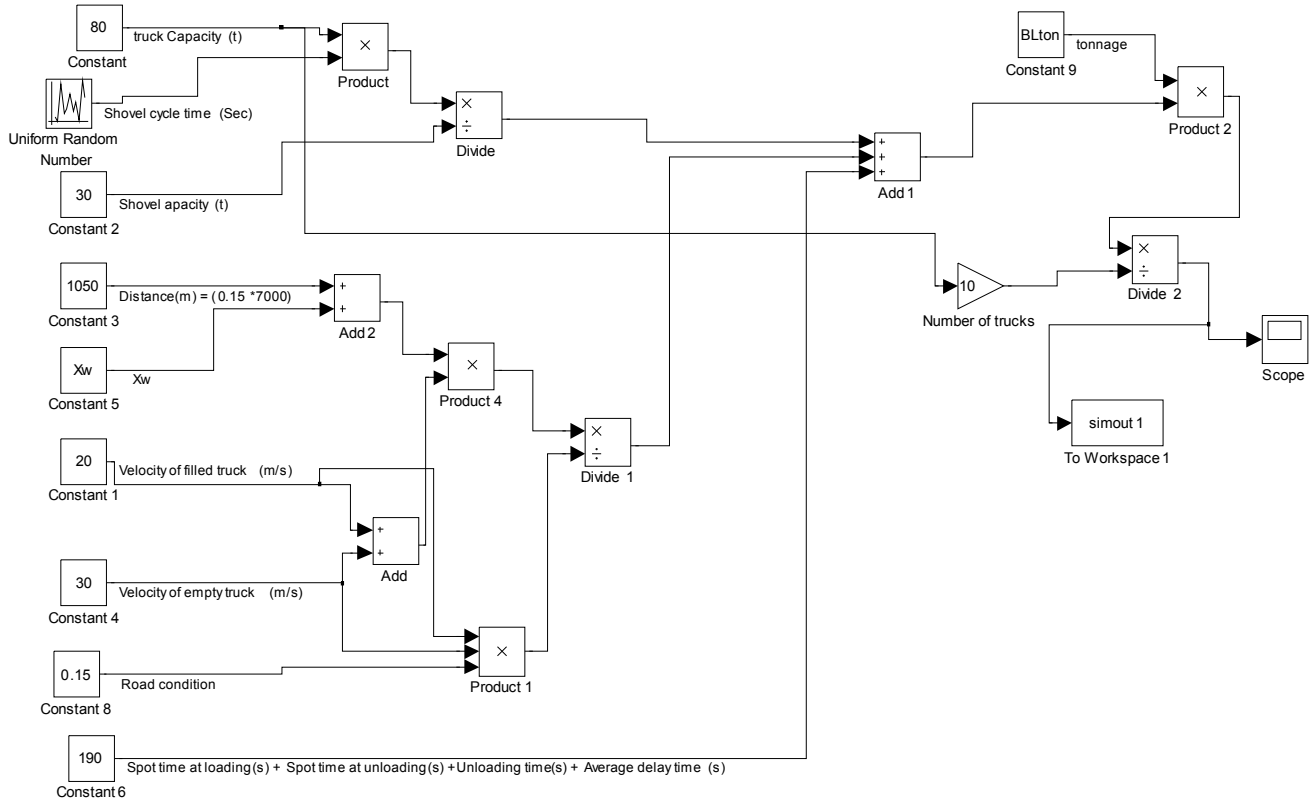


Fig 11. Simulink model for sensitivity analysis

Simulation was carried out for three different road conditions. Table 3 indicates truck velocity in fill and empty situation for each condition.

We assumed that there were 10 available trucks in the mine. Distance between each block and starting point of main road is calculated using Matlab code and is inserted as a matrix from X_w entrance. Tonnage of each block that has been calculated using Matlab code is inserted from BLton entrance.

Table 3. Velocity of truck for different conditions

Condition	$V_{t-fill} (m/s)$	$V_{t-empty} (m/s)$
1	20	30
2	14	25
3	10	18

There are two working shifts, day shift and night shift, which each shift is 8 hours and working days during a year is 350 days.

Figure 12 shows the necessary working days for blocks in each period under different conditions. Sum of the necessary days for each condition per period have been summarized in table 4.

Table 4. Duration of each period and project for different conditions

	Period 1 (day)	Period 2 (day)	Period 3 (day)	Period 4 (day)	Period 5 (day)	Duration of project (day)
Velocity condition1	142	172	170	171	172	826
Velocity condition2	181	219	216	218	219	1054
Velocity condition3	242	294	290	292	294	1411

The results show duration of project for conditions 1, 2 and 3 will be more than 2, 3 and 4 years, respectively. We want to find the effect of maintenance of road in working area on duration of project. For this purpose, the mine maintenance group increased the quality of ground for transportation in working area to 50% of main road quality using two dozers.

Necessary days for extraction of blocks of each period under different conditions after maintenance are shown in figure 13. Table 5 shows summary of project duration when quality of ground for transportation was increased in working area.

7. Conclusion

In the present project, I tried to explain how we could use mixed integer formulation for open pit mines production scheduling using Matlab. After finding the blocks extraction sequence, effect of road maintenance on duration of project has been considered. For this purpose, the truck velocity was considered as a function of road conditions.

The results show that deterioration of the road conditions has a significant affect on project duration. The project time increased from two years under velocity condition one to four years under velocity condition two.

In mines, most of the road problems are within the working areas where the extraction and blasting are taken place. Therefore, two different kinds of road conditions in working areas were considered. The results indicate when the quality of road in working area increases because of good maintenance, project duration shows a decrease of 32%.

On the other hand, many mines are paying more attention to tire care programs. For the surface mining business, tires represent the largest portion of a haul truck's hourly operating expenses. Good haul roads lead to reduced fuel consumption, higher vehicle speed, longer tire life, and more comfortable and safer riding.

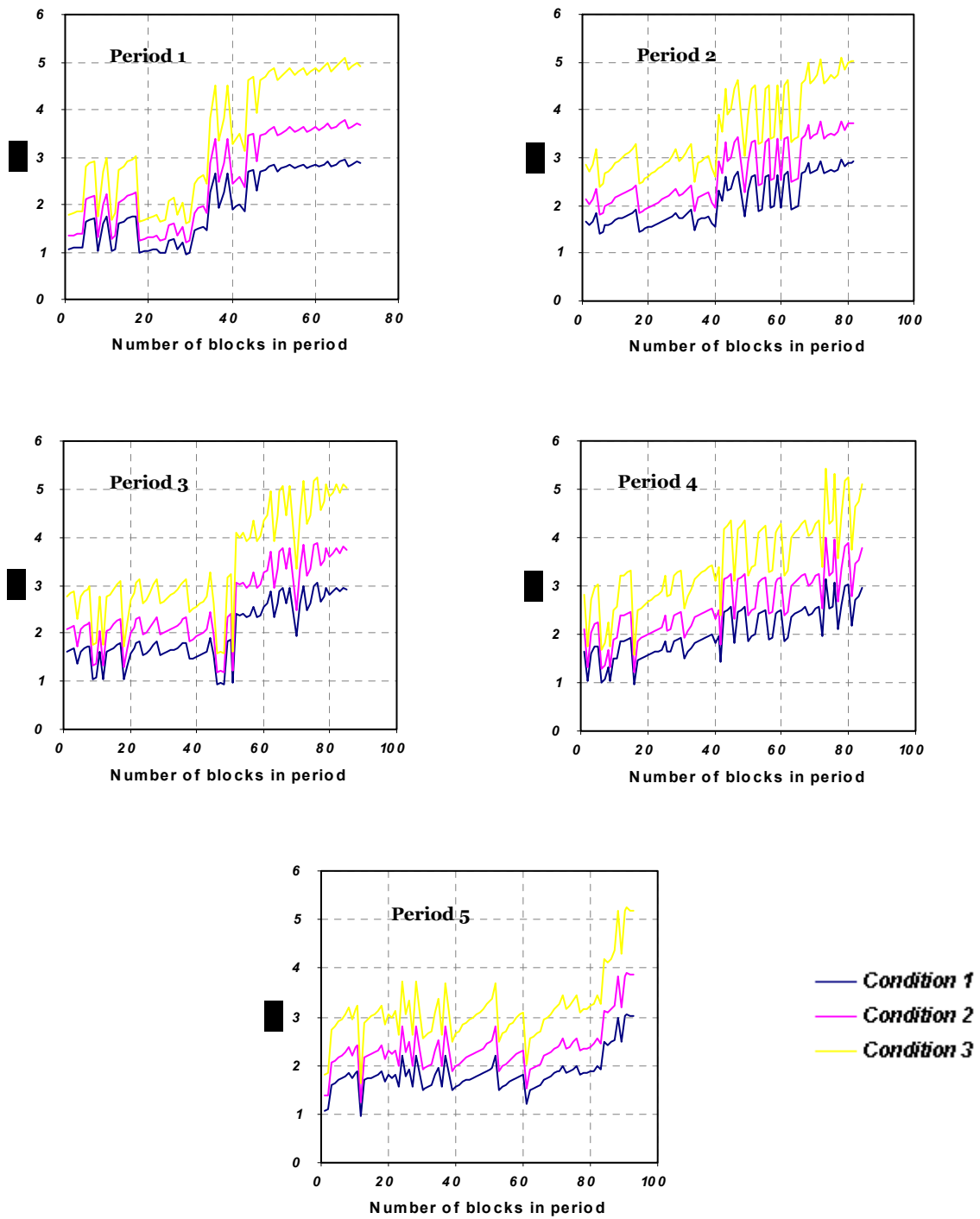


Fig 12. Necessary days for transportation of each block from working bench to destinations per period under different conditions.

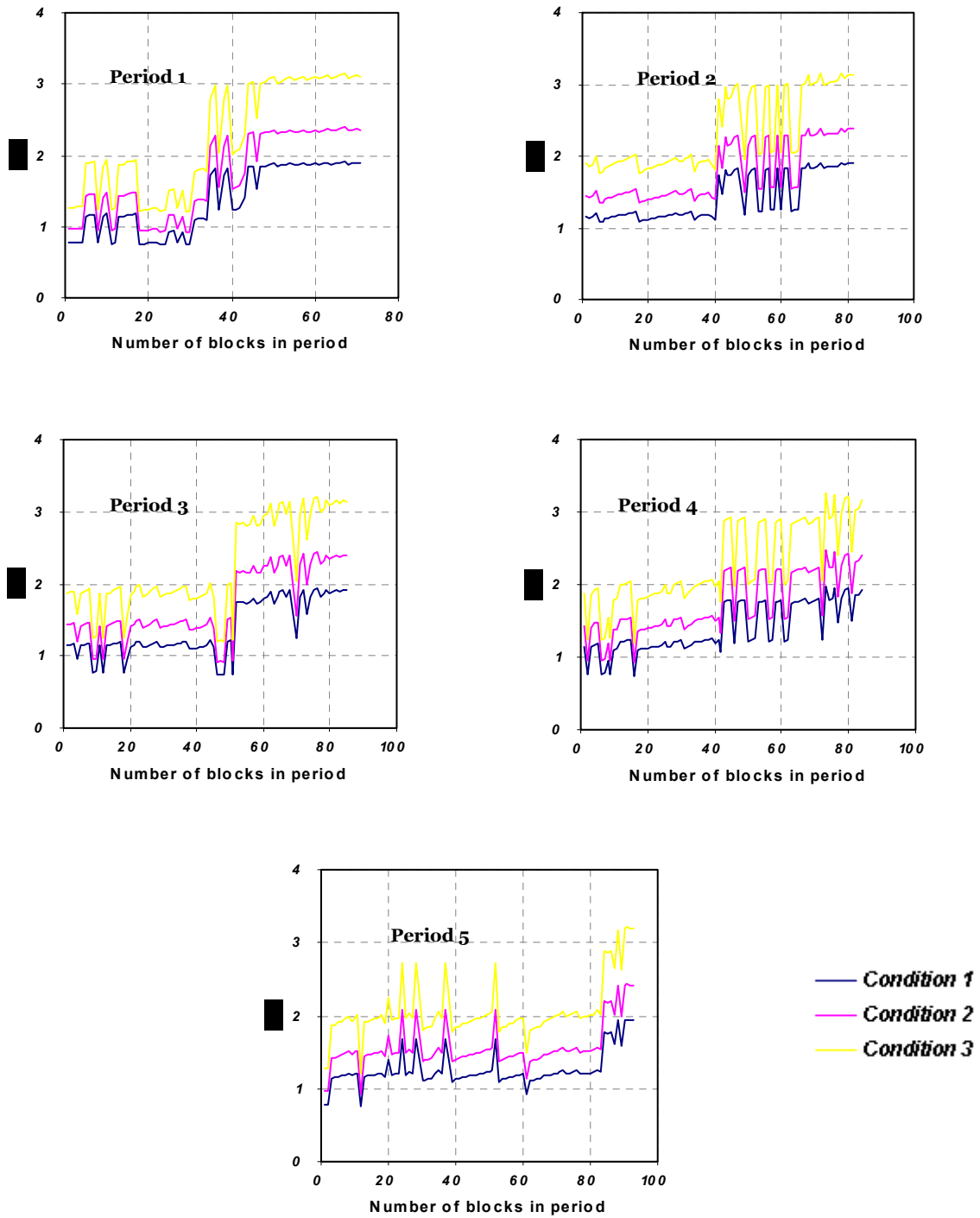


Fig 13. Necessary days for transportation of each block from working bench to destinations per period under different conditions when quality of ground in working area increases to 50% of main road quality.

Table 5. Duration of each period and project for different conditions

	period1 (day)	period2 (day)	period3 (day)	period4 (day)	period5 (day)	duration of project (day)
Velocity condition1	97	117	117	117	118	566
Velocity condition2	122	147	146	146	147	708
Velocity condition3	159	192	191	192	193	927

Difference between duration of project for two different road conditions is illustrated in figure 14.

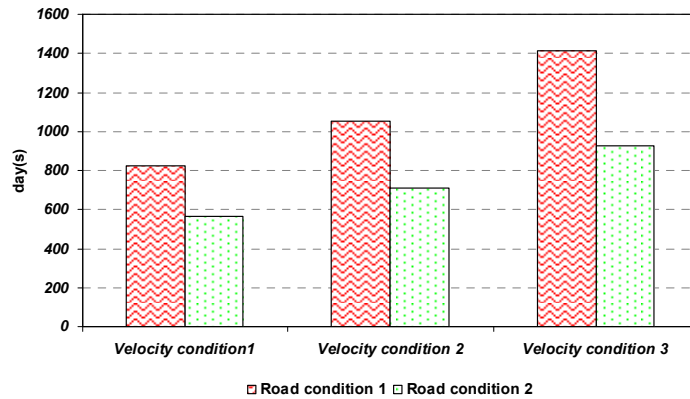


Fig 14. Duration of project for two different road conditions under different velocity conditions.

8. References

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9. Appendix

Link to: [MATLAB code of MIP model](#)

To run above Matlab code you need Matlab software and Tomlab toolbox. Then to run follow the below steps:

1. Copy three files: Blocks.m, MIP_solver_415.m and viewmatrix.m in a same folder
2. Run Matlab
3. Select c:\tomlab as current directory
4. Inside Matlab type **startup** and press enter (>> startup)
5. Change current directory to the folder that you copied three files inside it in step 1
6. Inside Matlab load Blocks.m >> load **Blocks**
7. Open MIP_solver_415.m and then run it.