Contents lists available at *Dergipark*

Journal of Scientific Reports-C

journal homepage: *https://dergipark.org.tr/en/pub/jsrc*

E-ISSN: 2717-8633 ***Sayı(Number) 8, Aralık(December) 2024***

ARAŞTIRMA MAKALESİ/RESEARCH ARTICLE

Geliş Tarihi(Receive Date): 27.05.2024 *Kabul Tarihi(Accepted Date): 09.06.2024*

A case study on operational planning for a mine-mill operation with stockpiling

Necmettin Çetin[a*]

[a]*Kütahya Dumlupınar University, Faculty of Engineering, Department of Mining Engineering, Kütahya, 43270, Türkiye, ORCID: 0000-0002-8897-172X*

Abstract

Mathematical modelling, and optimization are efficiently used in open pit mining problems, as it is the case of other engineering areas, business, and economic disciplines. One of the problems in this context is related to the role of stockpiles to serve maximization of the profit and minimization of the costs. In this paper, a short-term production plan for a mine-mill operation having a stockpile area is developed. The approach is based on network diagrams and linear programming method. Data set used in the application is hypothetical considering two months of duration. In the scenario, the milling facility nearby the mine is subjected to two stages material feeding located in the mining and milling areas. The objective is to minimize the costs while fulfilling the demands of the milling unit. LINGO software is used to evaluate the mathematical model. From the results of this study, it is concluded that there is no need for stockpiling operation at mill area for the stage 2 production process and the stockpile at mine area is required to satisfy the stage 1 production demand of 6,000 tons in month 2.
© 2023 DPU All rights reserved.
Keywords: Production Planning, Open Pit Mining, Network Models, Linear Programming, LINGO Software

Açık İşletme Tesisinde Cevher Stoklama İşleminin Üretim Planlaması Üzerine Bir Durum Çalışması

Öz

Matematik modelleme yada optimizasyon, ekonomi, işletme gibi disiplinleri ve diğer mühendislik alanlarında olduğu gibi madencilik sektöründe de yoğun olarak kullanılmaktadır. Bu alandaki problemlerden birisi de açık işletme tesislerindeki cevher stoklama işleminin planlanmasıdır. Bu makale de açık işletme tesisindeki cevher stoklama işleminin kısa dönemli (2 aylık) planlanması araştırılmıştır. Bunun için şebeke diyagramı ve doğrusal programlama metotları ile LINGO yazılım paketi kullanılmıştır. Amaç fonksiyon olarak tesisin kapasitesini karşılayan en düşük maliyetli cevher üretimi için iki adet stoklama alanı

planlanmıştır. Çalışmadan elde edilen sonuçlara göre, sadece maden sahasındaki stok alanının yeterli olduğuna ve tesis alanında bir stoklamanın gerekmediği kanısına varılmıştır.
© 2023 DPU All rights reserved.
Anahtar Kelimeler: Üretim Planlaması, Açık İşletme Madenciliği, Şebeke Modelleri, Doğrusal Programlama, LINGO Yazılımı

* Corresponding author. Tel.: +90 274 443 43 43
E-mail address: necmettin.cetin@dpu.edu.tr

1. Introduction

Mine planning requires sequential decisions and their implementation so that the assets of a mineral deposit can be extracted and processed economically and sustainably. As an engineering discipline, mining also relies on detailed mathematical calculations. Therefore, mathematical programming and estimating optimum solutions are of great importance. Linear and non-linear programming, game theory, transportation problems, assignment systems, networks, dynamic programming, etc. are some of approaches developed for this purpose.

Linear programming is used in the optimization of coal distribution problem where production is performed in six locations and forwarded to four consumption points at Garp Lignite Enterprise in Kütahya, Turkey [1].

Various shovel and truck operation approaches and optimization techniques for dispatching of trucks for different operating conditions are evaluated. They studied Orhaneli Open Pit Coal Mine in Turkey to find the optimum path for the trucks. It is shown the effect of the number of trucks and dispatching models on the cost of transporting the material by using linear programming [2].

Linear programming approach is proposed to determine the optimum distribution model in Kegalle, Sri Lanka [3]. The objective is to minimize the cost and Excel Solver is used. Mixed integer network a flow model is formulated for the underground gold mine in Red Lake, Ontario, Canada [4].

Linear Programming is one of the most commonly preferred mathematical tools for solving real optimization problems in many disciplines. Here, the optimal is unique through alternative combinations. The resources are scarce and mathematical behavior of the parameters are linear. Optimization exits as maximization or minimization. For example, maximization of revenue, production efficiency or minimization of costs, consumption of sources, distances, etc.

For the case study in this paper, a mathematical formula of linear program type to represent the open pit production planning for a mine-mill operation system with stockpiling problem is developed.

The problem in this case study is that mine manager wants an operating plan for the next two months which will maximize the profits (or minimize the costs) for his mine and operating system.

The mine can ship directly to the mill or stockpile. Stockpile is to supply the mill next month.

Mine capacity: 5 x 103 tons / month

Total reserves: 15 x 103 tons / month

Mining cost/ton: $1.00

Stockpiling cost (mill or mine): $0.10/ton

Rehandling from Stockpile: $0.15/ton

Transportation cost (mine-mill): $0.50/ton

The mill is a two stage operation and produces two marketable products (one after every stage). The mill ships directly to market from each stage.

As a principle, linear programming approach is based on the assumption that all the mathematical functions existing in the model are linear all [5]. The linear programs have commonly the following components:

• Decision variables: The decision variables represent the parameters for which the values to be estimated after solving the model. The symbols of them may be like X1, X2, X3, …. Xn. These variables are value carriers of unknown quantities (i.e. number of trucks in the fleet, amounts of ore or waste to be produced and so on).

• Objective function: It is the mathematical function written in terms of the decision variables which give maximum or minimum value after solving the entire functions. For instance, the objective function may aim at maximizing the revenues, minimizing the cost, as well as distance, time, energy consumption, etc.

• Resources Constraints: These functions represent the restrictions and limitations on raw materials, resources, time, manpower, requirements, etc. of the problem are expressed as inequalities or equations by using decision variables.

After describing the basic elements and idea of linear programming model, similarly, another approach, nonlinear programming model can be stated as the one including either a nonlinear objective function and/or any combination of nonlinear constraints. Linearity or nonlinearity seems to be the basic difference. However, the problem becomes more complex in nonlinear programming problems. Programming is a technique used to solve mathematical programming models with linear objective function and linear constraints. Linear type mathematical models including objective and constraint functions are solved and optimum can be found by the Simplex Algorithm approach developed by [6]. This technique, in fact, has a matrix base and are used to solve real or hypothetical linear programming models.

In this case study, an operational short-term production plan for a mine-mill operation with stockpiling option is developed as a case study.

2. Method and Input Data

2.1. Minimum Cost Network Flow Problems

Some type of problems can be structured on graphical networks and the paths, flows or spans on them can be maximized or minimized. Minimum cost flow problem has a primary and basic role through network flow problems. Application of minimum cost flow problems may find a large area in almost all industries such that manufacturing, transportation, energy distribution, marketing, communication, etc. In these problems, each node has a “supply”, or a “demand” given by some parameters. Each edge has some capacity, which is greater than zero. It is required to send the flow through the graph from between the supply nodes and the demand nodes to satisfy the demands regarding the limitations of the capacity. Finally, the objective of doing this in a manner which minimizes the total cost of the flow is attained. Here, network simplex yields the solution of any minimum cost network flow problem (MCNFP) where, the simplex is eligible, efficient, and easy to use. It is extremely important to formulate an LP as an MCNFP. A MCNFP can be defined by letting an example nomenclature given below [6].

x_{ij} = amount of flow from node i to node j through arc (i, j) (i.e. tons of ore produced/processed per month in the case study problem.)

b_i = net outflow and/or inflow at node i

c_{ij} = cost of transporting of flow per unit from node i to node j through arc (i, j)

U_{ij} =Upper bound on flow from node i to node j through arc (i, j) for each arc in the network

L_{ij} = Lower bound on flow from node i to node j through arc (i, j) for each arc in the network.

MCNFP can be formulated as (Winston, 2004):

$$Min \sum_{all\ arcs} cij\ .xij \tag{1}$$

Subject to:

$$\sum_j xij - \sum_k xki = b_i \qquad \text{for node I} \tag{2}$$

$L_{ij} \le x_{ij} \le U_{ij}$	for arc (i,j)	(3)
$x_{ij} \ge 0$	Non-negativity	(4)

3Constraints (2) mandate an equality between the net flow out of node i and bi. Besides, the constraint equations (2) should provide a balance in network flow. Group (3) constraints (3) enable restrictions and satisfaction equilibrium on the arc capacity. In our case study, all L_{ij} are initialized as zero. The constraints for the case study problem as MCNFP representation are given in Table 1. The first twelve constraints balance the flow through the nodes, and the last seventeen ones are for the capacity restrictions. The variable F_{ij} of flow balance equation gets +1 coefficient in the node I, -1 in the node j, and 0 in other flow balance equations. Node 1 is the supply node that has a capacity of +10.000 (tons of ore) while node 13 is the demand node having the same amount of 10.000 with negative sign. All other nodes have a capacity of zero.

Table 1. The MCNFP Incidence Matrix Representation of case study problem

F 1, 2	F 2, 3	F 2, 7	F 3, 4	F 4, 5	F 4, 6	F 6, 11	F 5, 13	F 4, 13	F 1, 8	F 7, 9	F 8, 9	F 9, 10	F 10, 11	F 11, 12	F 10, 13	F 12, 13	<=	rhs	Constraints
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	=	10000	Node_1
1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	=	0	Node 2
0	1	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	=	0	Node_3
0	0	0	1	-1	1	0	0	-1	0	0	0	0	0	0	0	0	=	0	Node_4
0	0	0	0	1	0	0	-1	0	0	0	0	0	0	0	0	0	=	0	Node_5
0	0	0	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	=	0	Node_6
0	0	1	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	=	0	Node_7
0	0	0	0	0	0	0	0	0	1	0	-1	0	0	0	0	0	=	0	Node_8
0	0	0	0	0	0	0	0	0	0	1	1	-1	0	0	0	0	=	0	Node_9
0	0	0	0	0	0	0	0	0	0	0	0	1	-1	0	-1	0	=	0	Node_10
0	0	0	0	0	0	1	0	0	0	0	0	0	1	-1	0	0	=	0	Node_11
0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	-1	=	0	Node_12
0	0	0	0	0	0	0	-1	-1	0	0	0	0	0	0	-1	-1	=	-10000	Node_13
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	<=	5000	Arc(1,2)
0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	<=	5000	Arc(2,3,)
0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	<=	5000	Arc(2,7)
0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	<=	5000	Arc(3,4)
0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	<=	4000	Arc(4,5)
0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	<=	7000	Arc(4,6)
0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	<=	7000	Arc(5,10)
0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	<=	2000	Arc(5,13)
0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	<=	2000	Arc(4,13)
0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	<=	5000	Arc(1,8)
0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	<=	5000	Arc(7,9)
0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	<=	5000	Arc(8,9)
0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	<=	7000	Arc(9,10)
0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	<=	7000	Arc(10,11)
0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	<=	4000	Arc(11,12)
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	<=	2000	Arc(10,13)
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	<=	4000	Arc(12,13)

All variables are nonnegative.

2.2. Input Data and Network Model of Case Study

Optimization problems such as production planning can be analysed by graphical or network representations. The input data for the case study problem is given in Table 2 and Table 3 below.

Table 2. The production cost data for case study

Stage	Production Cost ($/ton)	Capacity (ton 10^3) / month Low	Capacity (ton $x10^3$) /month High
1	1.08	2	7
2	0.75	2	4

Table 3. Market demands and prices for case study

Product	Month 1 (tons $x10^3$)	Month 2 (tons $x10^3$)	Price ($/ton)
1	2	2	6.000
2	2	4	7.000

The mathematical model for production planning problems can be described by linear programming methods. The case study problem has two stages (i.e. two months). It means that network diagrams can be used to solve this problem. The following network diagram summarizes the activities under consideration for the case study problem of mine-mill operations. The numbers on each arc represent the costs for each operation and permissible capacity on each potential node of the process. (Fig.1).

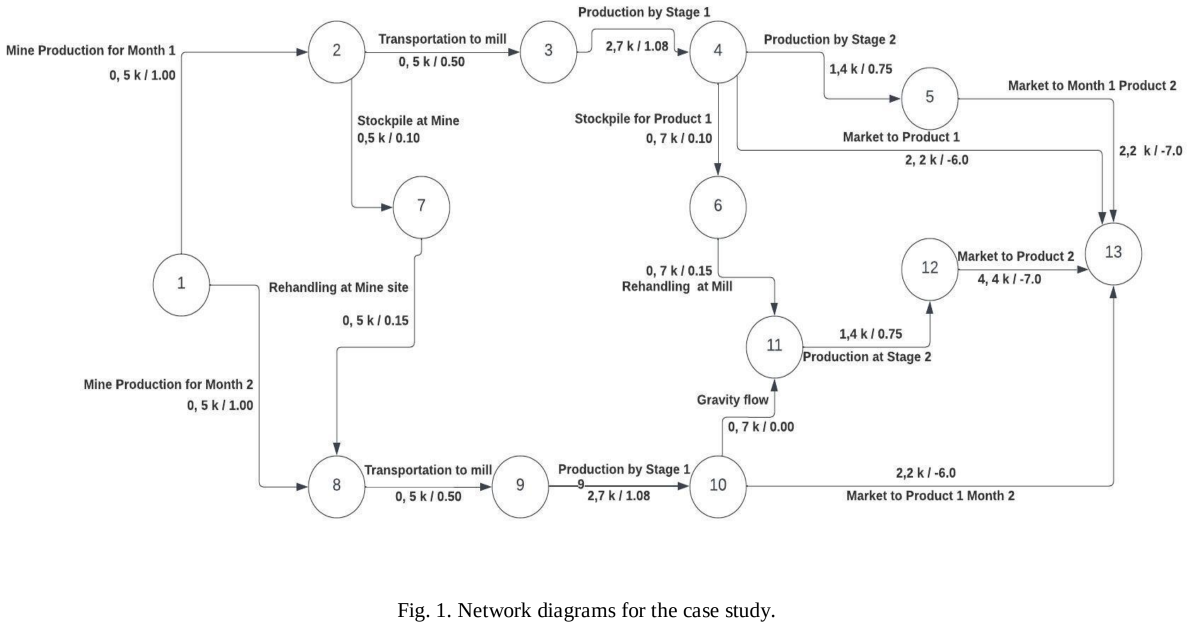

Fig. 1. Network diagrams for the case study.

2.3. LINGO Codes for the Case Study Problem

LINGO codes of the case study problem are given in Figure 2.

In line 2 of the codes given in Figure 2, the nodes are defined and they are linked to a net supply (flow out – flow in) with each node. Code line 12 is for data supplies. The arcs are defined in line 3 as a list and they are linked by a *capacity* (CAP), a *flow* (FLOW), and a *cost/unit shipped* (COST) with each arc in line 4. Line 11 is the code part where the cost of unit's shipping is entered. Line 6 generates the Objective function takes place in Line 6 and it is summed up over all arcs (*unit cost for arc*) x (*flow through arc*). Each arc's capacity constraints are stated in Line 7 where the arc data are entered in Line 13. Code Lines 8 and 9 generate the conservation-of-flow constraints for each node I. They imply that for each node I,

(flow out of node I) **-** *(flow into node I) = supply of node I.*

```
MODEL:
SETS:
   NODES / 1..13/    : SUPP;
   ARCS( NODES, NODES) /1,2  2,3  2,7 3,4 4,5 4,6 6,11 5,13 4,13 1,8 7,9 8,9 9,10 10,11, 11,12, 10,13, 12,13/
 : CAP, FLOW, COST;
ENDSETS

! The objective;

 MIN = @SUM( ARCS: COST * FLOW);
|
!  The Constraints;


 @FOR( ARCS(I, J): FLOW(I,J)<= CAP(I,J));
  @FOR( NODES( I): -@SUM(ARCS(J,I)  : FLOW(J,I))
  +@SUM( ARCS(I, J): FLOW( I, J))= SUPP(I));

! Here are the parameters;
DATA:
   CAP =    5000, 5000, 5000, 7000, 4000, 7000, 7000, 2000, 2000, 5000, 5000, 5000, 7000, 7000, 4000, 2000, 4000;
   SUPP =   10000, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, -10000 ;
   COST =   1,  0.50,  0.10,  1.08, 0.75,  0.10,  0.15,  -7, -6, 1, 0.15, 0.50, 1.08, 0.0, 0.75, -6, -7;
ENDDATA
END
```

Fig 2. LINGO Model for case study

All variables are nonnegative.

2.4. LINDO Model of the Case Study Problem

LINDO model of the case study is given in Figure 3.

```
MODEL:
[_1] MIN= FLOW_1_2 + 0.5 * FLOW_2_3 + 0.1 * FLOW_2_7 + 1.08 * FLOW_3_4 + 0.75 *
 FLOW_4_5 + 0.1 * FLOW_4_6 + 0.15 * FLOW_6_11 - 7 * FLOW_5_13 - 6 * FLOW_4_13 +
 FLOW_1_8 + 0.15 * FLOW_7_9 + 0.5 * FLOW_8_9 + 1.08 * FLOW_9_10 + 0.75 * FLOW_11_12
 - 6 * FLOW_10_13 - 7 * FLOW_12_13;
[_2] FLOW_1_2 <= 5000;
[_3] FLOW_2_3 <= 5000;
[_4] FLOW_2_7 <= 5000;
[_5] FLOW_3_4 <= 7000;
[_6] FLOW_4_5 <= 4000;
[_7] FLOW_4_6 <= 7000;
[_8] FLOW_6_11 <= 7000;
[_9] FLOW_5_13 <= 2000;
[_10] FLOW_4_13 <= 2000;
[_11] FLOW_1_8 <= 5000;
[_12] FLOW_7_9 <= 5000;
[_13] FLOW_8_9 <= 5000;
[_14] FLOW_9_10 <= 7000;
[_15] FLOW_10_11 <= 7000;
[_16] FLOW_11_12 <= 4000;
[_17] FLOW_10_13 <= 2000;
[_18] FLOW_12_13 <= 4000;
[_19] FLOW_1_2 + FLOW_1_8 = 10000;
[_20] - FLOW_1_2 + FLOW_2_3 + FLOW_2_7 = 0;
[_21] - FLOW_2_3 + FLOW_3_4 = 0;
[_22] - FLOW_3_4 + FLOW_4_5 + FLOW_4_6 + FLOW_4_13 = 0;
[_23] - FLOW_4_5 + FLOW_5_13 = 0;
[_24] - FLOW_4_6 + FLOW_6_11 = 0;
[_25] - FLOW_2_7 + FLOW_7_9 = 0;
[_26] - FLOW_1_8 + FLOW_8_9 = 0;
[_27] - FLOW_7_9 - FLOW_8_9 + FLOW_9_10 = 0;
[_28] - FLOW_9_10 + FLOW_10_11 + FLOW_10_13 = 0;
[_29] - FLOW_6_11 - FLOW_10_11 + FLOW_11_12 = 0;
[_30] - FLOW_11_12 + FLOW_12_13 = 0;
[_31] - FLOW_5_13 - FLOW_4_13 - FLOW_10_13 - FLOW_12_13 = - 10000;
END
```

Fig 3. LINDO Model for the case study

In figure 3 with LINDO model, Line 1, the objective function is specified as a Minimization of the total cost of mining, transportation, stock-piling, re-handling and processing for the case study problem. It is noted that the coefficients are all negative for the demand node 13 only while all other nodes have positive coefficient in the objective function. Lines 2- 19 are arc capacity constraints for all arcs in the network and the other rest including lines 20-31 are the node flow balance constraints in the network problem.

3. Results and Discussion

When the LP model of the case study problem was solved both on LINDO and LINGO. it was found that the optimal value of the objective function was equal to – 35,950 $ meaning that negative total cost is in fact a positive income for the operational plan. It means that the mining company will earn a profit of 35,950 $ by the production schedule for the two months' duration from this mine-mill operational plan (i.e., according to the minus signs that are assigned to the income from the sales of both product 1 an d product 2 while all other cost parameters are assumed to be positive). The output results of the decision variables for case study problem obtained by LINGO and LINDO software is summarized in Table 4. As it can be seen from Table 4, there is no need for stockpiling operation at mill site for the stage 2 production process and the stockpile at mine site is required to satisfy the production stage 1 demand of 6,000 tons in month 2.

Table 4. Output Data obtained for case study problem by LINGO and LINDO

Decision Variables	**Cost Coefficient ($/ton)**	**Value** (Production rate) **(tons/month)**	**Capacity (tons/month)**	**Activity**
FLOW(1, 2)	1.00	5000	5000	Mine Production in Month 1
FLOW(2, 3)	0.50	4000	5000	Transportation mill
FLOW(2, 7)	0.10	1000	5000	Stockpiling at mine site
FLOW(3, 4)	1.08	4000	7000	Production at stage 1
FLOW(4, 5)	0.75	2000	4000	Production at stage 2
FLOW(4, 6)	0.10	0	7000	Stockpiling for product 1
FLOW(6, 11)	0.15	0	7000	Rehandling for product 1
FLOW(5, 13)	-7.00	2000	2000	Market for product 2 in month 1
FLOW(4, 13)	-6.00	2000	2000	Market for product 1 in month 1
FLOW(1, 8)	1.00	5000	5000	Mine Production in Month 2
FLOW(7, 9)	0.15	1000	5000	Rehandling for month 2
FLOW(8, 9)	0.50	5000	5000	Transportation mill
FLOW(9, 10)	1.08	6000	7000	Production at stage 1
FLOW(10, 11)	0.00	4000	7000	Gravity Flow
FLOW(11, 12)	0.75	4000	4000	Production at stage 2
FLOW(10, 13)	-6.00	2000	2000	Market for product 1 in month 2
FLOW (12,13)	-7.00	4000	4000	Market for product 2 in month 2
Global Optimal Solution		**-35950.00**		

4. Conclusion

In this paper, production planning problems in open pit mining were modelled and solved using two softwares called LINGO and LINDO. An operating short-term production plan was developed on a hypothetical case study for the following two months' duration which maximizes profits (or equivalently minimizes cost) for a mine-mill operation system with stockpiling.

As seen from the optimization process, the following main results could be derived:
a) The production planning problems in mining operations can be solved by mathematical programming methods such as Linear Programming to reduce the total operating cost during the life of mines.
b) Network flow models can be applied to other areas in open pit or underground mining industry such as open pit truck dispatching problem, blasting pattern design optimization, transportation network optimization and like many other optimization problems.
c) Stockpiling options provides great operational flexibility for production planning problems in mine-mill operations since the planning parameters are highly sensitive to variations in costs and prices.
d) Open pit mining systems involve many financial factors such as operating cost, revenues, total capital investment etc. that are highly stochastic in nature and, therefore, they should be modelled accordingly.

Acknowledgment

No support has been given

References

[1] B. Elevli, N. Uzgören and A. Sezgin, "Coal distribution optimization by utilizing linear programming", *Engineering & Arch. Faculty*. Eskisehir Osmangazi University, Vol. XX, No:1, 2007.
[2] S.G. Ercelebi and A. Bascetin, "Optimization of shovel-truck system for surface mining", *J. South. Afr. Inst. Min. Metall.*, Vol:109, July, pp:.433-439, 2009.
[3] A. M. P. Chandrasiri, D. M. Samarathung, "Application of Minimum Cost Flow Problem: A Case Study of Crown Distributors in Kegalle, Sri Lanka", *IJSER-Int. J. Eng. Res*, vol. 8, Jan, 2017.
[4] S. E. Gliwan and K. Crowe, "A network flow model for operational planning in an underground gold mine", *Mining* 2022, *2*(4), 712-724; https://doi.org/10.3390/mining2040039.
[5] W. L. Winston, Operations research – applications and algorithms, Fourth Edition, *Thomson Brookscole/Cole*, 2004
[6]G. B. Dantzig, Linear programming and extensions, *Princeton University Press*, Princeton, NJ, 1963.