

**An Integrated Approach to Mine Planning
and Equipment Selection/Allocation**

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Abstract: This paper attempts to incorporate equipment selection/allocation into the optimization of open pit mine production scheduling. Equipment selection has been conventionally treated as a separate procedure in mine planning, and this separation may lead to undervaluing a mining venture or may generate schedules that may not be compatible deposit characteristics. The motivation for this work is the fact that the equipment cannot be selected without knowing production rates and the sequencing of blocks to be mined; similarly mining blocks cannot be sequenced without selecting equipment. Thus, block sequencing, ore-waste discrimination and equipment selection would be optimal if optimized concurrently. The concurrent optimization of the above sub-problems is formulated herein as a mixed integer programming (MIP) optimization problem. Equipment operating costs, which have been included in mining costs in previous studies, are used as coefficients in the proposed MIP optimization formulation. The reliability of the optimal solution requires comprehensive cost engineering, which leads to the classification of equipment costs into three groups: depreciation, preventive maintenance and other operational costs. The objective is to maximize the net present value (NPV) of a project under the constraints of capacities, access, equipment relations and matching. Afterwards, mining block extraction times and destinations, as well as equipment types to be used are determined. A case study demonstrates the model developed for a gold mine. The findings show that the optimization model can be used in the mine planning procedures.

Key Words: Mine planning, block sequencing, ore-waste discrimination, equipment selection, mixed integer programming.

1 Introduction

Mine planning research has evolved towards total optimization along with the synergy created by the initiation of new computing and optimization technologies. Mine production scheduling refers mostly to solving three sub-problems, namely: extraction time of a block (sequencing), decision on the destination of extracted block (ore-waste discrimination) and the amount of material extracted in a given period (production rates) (Hochbaum and Chen, 2000; Caccetta and Hill, 2003; Kumral and Dowd, 2005; Sarin and West-Hansen, 2005; Newman and Kuchta, 2007; Boland et al., 2008; Kumral, 2011). Furthermore, there are closely related aspects, such as equipment selection, which should be combined with mine production scheduling. These problems are solved sequentially (Figure 1), however, there is a known “chicken or the egg” dilemma: to optimize any sub-problem, other sub-problems should be solved previously. For example, to determine production rates and equipment, block sequencing should be known first. However, to sequence blocks, the cut-off grade should be known. In order to know cut-off grades, the cost structure of operations, that are functions of production rates and equipment, should be determined first.

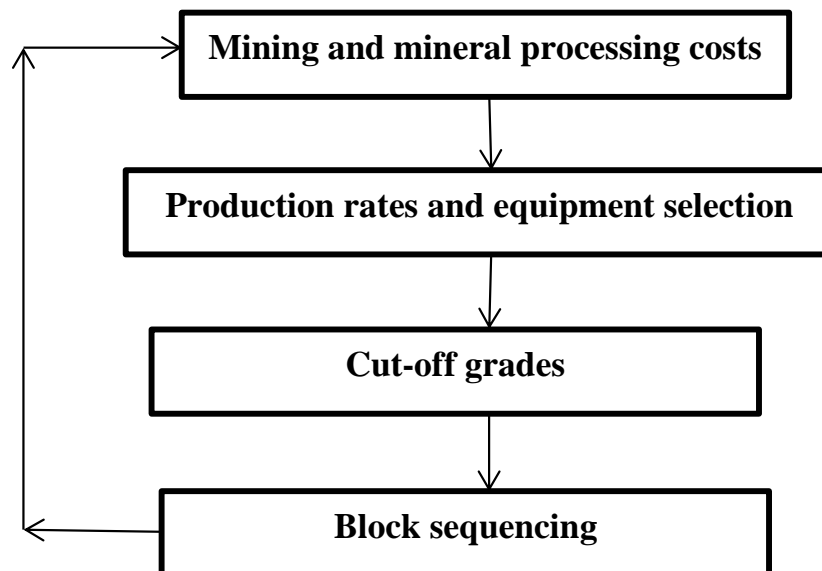


Figure 1: Sequential mine planning procedure

In other words, these problems are interdependent and should be solved simultaneously. This paper attempts to solve block sequencing, ore-waste discrimination and equipment selection concurrently for given capacities. The problems relating the equipment can be of two types: (1) selection, allocation and dispatching and (2) reliability and maintenance. Equipment selection and allocation are strategic decisions. Dispatching is related to short-term planning and includes instantaneous decisions. In an open pit mining context, types, numbers, size, compatibility of the equipment, the quantity of material to be transported and cycling times are main concerns about the selection and allocation problem. The dispatching focuses on maximizing equipment utilization considering availability, cycling and waiting times. Given that the selection, allocation and dispatching problems are closely related to availability and operating costs, reliability analysis and maintenance strategies can be seen as integral parts of the problems.

In the past, many research efforts have been devoted to solve different patterns of the problems. Michiotis et al. (1998) expressed the selection of excavation equipment as minimizing time required for the excavation of a bench through zero-one integer programming. Topal and Ramazan (2010) presented a mixed integer programming model for scheduling a fixed fleet of mining trucks such that maintenance cost is minimized. Burt et al. (2011) developed an integer model, which is equipment selection with heterogeneous fleets for multi-period scheduling. Unlike previous research, this paper considers a cost structure with respect to equipment age, meeting production requirement and allowing multi-period planning. Known block sequencing

was critical assumption in this research. Fiorini et al. (2008) formulated truck allocation problem to satisfy ore target in a main pile in the case of multiple production face and multiple variables.

There are also research on mine equipment reliability and maintenance (Kumar et al., 1993; Louit et al., 2001; Roy et al., 2001; Vagenas and Nuziale, 2001; Hall et al., 2003; Vagenas et al., 2003; Barabady et al., 2008; Kumral, 2009). These researches mostly focused on the analysis of mean time to failure (MTTF) and mean time to repair it (MTTR). In the first stage of these researches, the system is defined and sub-systems are identified and coded. Then, data are analyzed for verification of the identically and independently distributed (IID) assumption. A theoretical probability distribution is fitted to MTTF and MTTR data for sub-systems.

Elbrond and Soumis (1987) had researched the relation between production scheduling and equipment selection long time ago. This paper advances on this relation through an optimization model. The problem is formulated as the maximization of net present value of the project under the depreciation, material-equipment compatibility, capacity and access constraints relating block sequencing and equipment selection.

2 Cost analysis attributed to equipment selection

In cost engineering, an analyst should firstly recognize difference between the accounting treatment of costs and the economic treatment of costs (Runge, 1999). During the research, only real costs are considered; fuel, repair and maintenance, tire, depreciation, and labor cost are important costs considered in the estimation of operating costs.

The costs are a function of the extracted material and firm characteristics such as size and strategy. Figure 2 illustrates a typical equipment cost evolution on time.



Figure 2: Operation costs versus time

First, the operating costs increase by time, where they then reach a peak where maintenance is required and its cost is incurred. After maintenance, the operating cost decreases immediately. Finally, this cycle is repeated with a trend. In this paper, the costs are assessed in three groups:

a. Depreciation costs

A double-declining-balance method is considered for the depreciations. The method is an accelerated method since a large part of the cost is expensed at early periods of the life of the equipment. The reason behind this method is that the equipment is more productive in initial periods and their productivity declines continuously. The equipment will be generating more revenue in early periods of life.

b. Preventive maintenance costs

Two types of maintenance activities are implemented: Preventive (time-based activities) and just-in-time (operate to failure). In this section, annual preventative maintenance conducted is considered on the

basis of equipment reliability. Just-in-time maintenance is treated as an operational cost. Using historical data, a reliability function is fitted to each loader and truck type. For example, the reliability function of two-parameter Weibull distribution is given as:

$$R(t) = e^{-\left(\frac{t}{\beta}\right)^\alpha} \quad (1)$$

where $R(t)$ is the equipment at time t , β is scale parameter of the equipment and α is shape parameter of the equipment. Similarly, the reliability function of two-parameter exponential distribution is given as:

$$R(t) = e^{-\lambda(t-\gamma)} \quad (2)$$

where λ is inverse scale parameter and γ is location parameter. As reliabilities decreases by time, preventive maintenance costs increase. Maintenance cost is estimated from the reliability levels.

c. Other operation costs

Operational costs are labor, fuel, just-in-time maintenance, oil, greases, tire wear, replacement, wear items and repair parts. Equipment and road characteristics are main factors affecting operation costs. Economies of scale in larger companies lead to reduced average operating costs, i.e. larger companies incur lower average cost per distance. Equipment operation costs can be classified two parts: running cost (e.g. fuel, oil, tire and maintenance) and standing costs (e.g. license, insurance and interests). Speed and equipment size are identified as the most important factors in fuel consumption. In mine equipment selection, allocation and dispatching, the fixed cycle times are used (the speed is assumed as the fixed). Therefore, the main problem is to select equipment among different types and models such that the equipment is compatible with each other (matching factor). To estimate equipment operational costs, the following firm characteristics should be also known:

- *Firm size*

Levinson et al. (2004) used two variables to calculate operating costs: distance/truckload (ϑ) and the number of truckloads (τ).

- *Firm strategy*

To ensure equipment matching and deliveries on time, a penalty system is initiated. Financial penalty (ω) remarks that equipment performance is governed by various safety and economic standards.

- *Firm type*

This indicates type of operation and equipment ownership (φ) such as outsourcing, joint venture or firm possession.

- *Economies of scope*

Economies of scope refer to the potential cost savings from joint production (ε). These are changes in average costs because of changes in the mix of output between two or more products. To calculate operational costs, Cobb-Douglas model (Greene, 2003) is used because it generates better fits than linear models. For trucks, the model is given as:

$$Cost = e^{\beta_0} (\vartheta)^{\beta_1} \tau^{\beta_2} (e^\omega)^{\beta_3} (e^\varphi)^{\beta_4} (e^\varepsilon)^{\beta_5} \quad (3)$$

The coefficient β of the independent variable is the elasticity of cost with respect to that independent variable such as production quantity. When the Cobb-Douglas model is transformed to log linear form:

$$\ln(Cost) = \beta_0 + \beta_1 \ln(\vartheta) + \beta_2 \ln \tau + \beta_3 \omega + \beta_4 \varphi + \beta_5 \varepsilon \quad (4)$$

The same approach can be adopted for the loader operating costs. By the selection of appropriate β 's, this equation can be used to calculate the operating costs. However, the Cobb-Douglas cost function

cannot be used directly for heterogeneous fleet and multi-period planning. In this research, the fact that the operation costs based on the Cobb-Douglas equation should be smaller than the operation costs based on the consideration of equipment items separately is utilized in the MIP model. Given the capacities and transportation distances, the operation cost from the Cobb-Douglas function can be calculated in general. This cost is then used in the MIP formulation as the constraints.

3 Model formulation

The objective is to maximize the NPV of a mining venture such that the blocks are sequenced, ore - waste discrimination is made and the equipment is selected.

Assumptions

1. All trucks and loaders to be selected are brand new.
2. Double-declining-balance method is used for depreciations.
3. There is one production face.
4. Both preventive and just-in-time maintenance strategies are implemented.
5. The equipment life is equal or longer than time horizon (T) under consideration

Indexes

$t = 1, 2, \dots, T$	T denotes the number of periods to be scheduled
$n = 1, 2, \dots, N$	N denotes the number of blocks
$d = 1, 2, \dots, D$	D denotes the number of destinations
$k = 1, 2, \dots, K$	K denotes the number of truck types
$m = 1, 2, \dots, M$	M denotes truck model in types K
$s = 1, 2, \dots, S$	S denotes the number of loader types
$h = 1, 2, \dots, H$	H denotes loader model in types S
$i = 1, 2, \dots, IMAX$	$IMAX$ is the number of maximum allowable trucks in any model of type
$j = 1, 2, \dots, JMAX$	$JMAX$ is the number of maximum allowable loaders in any model of type

Data

r_{tnd}	is the present value of the profit of block n in the period t for destination d
C_{tkmi}	is the present value of annual operation costs for truck i of model m of type k in period t
a_{tkmi}	is the depreciation cost for truck i of model m of type k in period t
τ_{tkmi}	is the present value of the maintenance cost for truck i of model m of type k in period t
e_{tshj}	is the present value of the annual operation cost for loader j of model h of type s in period t
g_{tshj}	is the depreciation cost for loader j of model h of type s in period t
φ_{tshj}	is the present value of the maintenance cost for loader j of model h of type s in period t
IA_{tkm}	is the present value of the investment cost for truck m of type k
SVA_{km}	is the present value of the scrap value for truck m of type k
IB_{tsh}	is the present value of the investment cost for loader s of type h
SVB_{sh}	is the present value of the scrap value for loader s of type h
p_{tkmi}	is the annual capacity for truck i of model m of type k in period t
w_{tshj}	is the annual capacity for loader j of model h of type s in period t
ct_{kmi}	is the capacity per hour (60 min / cycle time of truck * physical capacity of truck)
cl_{shj}	is the capacity per hour (60 min / cycle time of loader * physical capacity of loader)
v_{km}	is the physical capacity of truck model m of type k
u_{sh}	is the physical capacity of loader model s of type h

$Cost_{truck}$	is the operational cost of trucks obtained by the Cobb-Douglas cost function for the selected equipment configuration
$Cost_{loader}$	is the operational cost of loaders obtained by the Cobb-Douglas cost function for the selected equipment configuration
f_n	is the tonnage of block n
Upp_d	is the capacity of destination d
Low_d	is the minimum limit for material to be extracted

Variables

x_{tnd} binary variable if block n is sent to destination d in period t , it takes 1. Otherwise, it is zero:

$$x_{tnd} \in \{0, 1\} \quad t = 1, \dots, T; n = 1, \dots, N \quad \text{and} \quad d = 1, \dots, D \quad (5)$$

$y_{shj}^{kmi}(t)$ binary variable if truck i of model m of type k and loader j of model h of type s in period t are selected and matched, it takes 1. Otherwise, it is zero:

$$y_{shj}^{kmi}(t) \in \{0, 1\} \quad t = 1, \dots, T; \quad k = 1, \dots, K; \quad m = 1, \dots, M; \quad i = 1, \dots, IMAX; \\ s = 1, \dots, S, \quad h = 1, \dots, H \quad \text{and} \quad j = 1, \dots, JMAX \quad y_{sh}^{km}(t) \quad (6)$$

Objective function

$$\text{Max} \sum_{t=1}^T \sum_{n=1}^N \sum_{d=1}^D r_{tnd} x_{tnd} - \sum_{t=1}^T \left[\left[\sum_{k=1}^K \sum_{m=1}^M \sum_{i=1}^{IMAX} (c_{tkmi} + a_{tkmi} + \tau_{tkmi}) \right] \right. \\ \left. + \left[\sum_{s=1}^S \sum_{h=1}^H \sum_{j=1}^{JMAX} (e_{tshj} + g_{tshj} + \varphi_{tshj}) \right] \right] y_{shj}^{kmi}(t) \quad (7)$$

Subject to:

1. The selected truck or loader should be depreciated fully. That is, it is guaranteed that equipment is used in full.

$$\sum_{t=1}^T a_{tshj} y_{shj}^{kmi}(t) = IA_{km} - SVA_{km} \quad k = 1, \dots, K; \quad m = 1, \dots, M; \\ i = 1, \dots, IMAX; \quad s = 1, \dots, S; \quad h = 1, \dots, H \quad \text{and} \quad j = 1, \dots, JMAX \quad (8)$$

$$\sum_{t=1}^T g_{tshj} y_{shj}^{kmi}(t) = IB_{sh} - SVB_{sh} \quad k = 1, \dots, K; \quad m = 1, \dots, M; \\ i = 1, \dots, IMAX; \quad s = 1, \dots, S; \quad h = 1, \dots, H \quad \text{and} \quad j = 1, \dots, JMAX \quad (9)$$

2. If a loader and a truck are matched, this should be continued in the following years until end of time horizon under consideration.

$$y_{shj}^{kmi}(l) \geq y_{shj}^{kmi}(l-1) \quad \text{if} \quad y_{shj}^{kmi}(1) \geq 1 \quad \text{for} \quad l = 2, \dots, T; \quad k = 1, \dots, K; \quad m = 1, \dots, M; \\ i = 1, \dots, IMAX; \quad s = 1, \dots, S; \quad h = 1, \dots, H \quad \text{and} \quad j = 1, \dots, JMAX \quad (10)$$

3. The selected fleet should have capacity to load and haulage the extracted material.

$$\sum_{k=1}^K \sum_{m=1}^M \sum_{i=1}^{IMAX} v_{km} D_{tkmi} C_{tkmi} y_{shj}^{kmi}(t) \geq \sum_{n=1}^N \sum_{d=1}^D f_n x_{tnd} \quad t = 1, \dots, T; \quad s = 1, \dots, S; \\ h = 1, \dots, H \quad \text{and} \quad j = 1, \dots, JMAX \quad (11)$$

$$\sum_{s=1}^S \sum_{h=1}^H \sum_{j=1}^{JMAX} u_{sh} w_{shj} C_{shj} y_{shj}^{kmi}(t) \geq \sum_{n=1}^N \sum_{d=1}^D f_n x_{tnd} \quad t = 1, \dots, T; \quad k = 1, \dots, K; \\ m = 1, \dots, M \quad \text{and} \quad i = 1, \dots, IMAX \quad (12)$$

4. The capacity of truck fleet should be exceed the capacity of loader which is matched in each period.

$$\sum_{k=1}^K \sum_{m=1}^M \sum_{i=1}^{IMAX} v_{km} D_{tkmi} C_{shj} y_{shj}^{kmi}(t) \geq w_{shj} u_{sh} C_{shj} y_{shj}^{k1m1i1}(t) \quad t = 1, \dots, T; \quad k1 = 1, \dots, K; \\ m1 = 1, \dots, M; \quad i1 = 1, \dots, IMAX; \quad s = 1, \dots, S; \quad h = 1, \dots, H \quad \text{and} \quad j = 1, \dots, JMAX \quad (13)$$

5. The selected and allocated equipment should be compatible with each other such that the loader capacity cannot be larger than the truck capacity in the matched equipment.

$$v_{km} y_{shj}^{kmi}(t) \geq u_{sh} y_{shj}^{kmi}(t) \quad t = 1, \dots, T; \quad k = 1, \dots, K; \quad m = 1, \dots, M; \quad i = 1, \dots, IMAX; \\ s = 1, \dots, S; \quad h = 1, \dots, H \quad \text{and} \quad j = 1, \dots, JMAX \quad (14)$$

6. A truck can be allocated to only one loader.

$$\sum_{s=1}^S \sum_{h=1}^H \sum_{j=1}^{JMAX} y_{shj}^{kmi}(t) \leq 1 \quad t = 1, \dots, T; \quad k = 1, \dots, K; \\ m = 1, \dots, M \quad \text{and} \quad i = 1, \dots, IMAX \quad (15)$$

7. Access constraint

$$\sum_{d=1}^D x_{tkd} \geq \sum_{d=1}^D x_{tnd} \quad t = 1, \dots, T; \quad n = 1, \dots, N \quad \text{and} \quad k \in K_j \quad (16)$$

8. Destination capacity constraint

$$\sum_{n=1}^N f_n x_{tnd} - Upp_d \leq 0 \quad t = 1, \dots, T \quad \text{and} \quad d = 1, \dots, D \quad (17)$$

$$\sum_{n=1}^N f_n x_{tnd} - Low_d \geq 0 \quad t = 1, \dots, T \quad \text{and} \quad d = 1, \dots, D \quad (18)$$

9. Block conservation constraint

$$\sum_{t=1}^T \sum_{d=1}^D x_{tnd} \leq 1 \quad n = 1, \dots, N \quad (19)$$

4 Case study

The performance of the proposed approach is tested in a case study. Initial data comprised a set of 10 drill-holes, the cores from which had been assayed for Au (Figure 3).

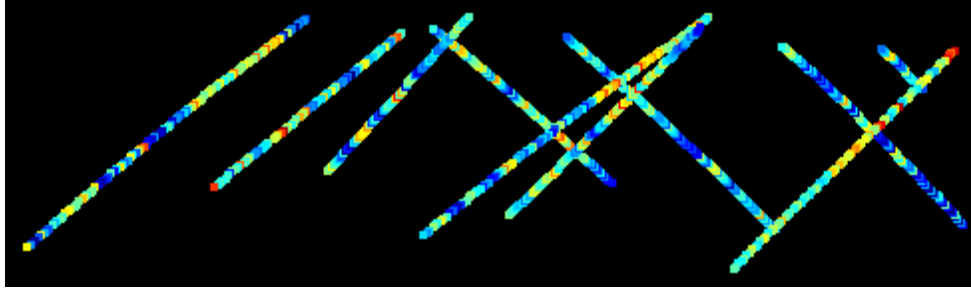


Figure 3: Drillhole locations

Additional information on the data can not be provided due to confidentiality reasons. A three-dimensional orebody model is created. Mining blocks are 10 m (EW) * 12 m (NS) * 10 m. There are 32256 blocks. Block economic values, which are used as input data in the optimization process, are calculated for each destination. The parameters used to calculate block economic values are given in Table 1.

Table 1: Input data

Number of periods	6		
Number of destinations	3 (one for waste and two for processing)		
Capacities	1000	500 (in blocks for Destination 2 and 3)	
Number of blocks	32256		
Mining cost (\$/tonne)	1.5	1.5	1.5 (in destinations)
Processing cost (\$/tonne)	0	18	35 (in destinations)
Recoveries (%)	0.0	0.75	0.90
Gold price (\$/g)	50		
Block tonnage (tonne)	5000		
Discount rate (%)	10		

In this case study, there are three routes: waste dump, low grade and high grade processing. Note that truck- and loader- related costs are subtracted from block economic values. Given that the mining cost is taken as the fixed value and applied to all blocks in conventional mine planning, this does not make important difference. Hence, the equipment costs are transferred from the block sequencing part to the equipment selection part in the objective function. In this case, mining cost consists of drilling, blasting and other mine-specific operational costs. In this research, four brands of trucks and three brands of loaders are considered; each brand of trucks and loaders has three models with varying capacities. There are therefore 12 different trucks and 9 different loaders. A maximum of ten trucks or loaders can be selected from each type of each brand. Due of commercial reasons, names of brands and models are not given. Truck and loader capacities are only provided.

To calculate the depreciation costs, the required depreciation rate and the equipment life are given in Tables 2 and 3. Using these values, annual depreciation for the equipment is calculated and used as parameters in the model formulation. Since the declining-balance method (reducing balance method) is used, the depreciation costs are in descending order. Given that the equipment is more efficient in its early life, the selection of declining-balance method is reasonable. Moreover, higher allocation in early years is important in the optimization part. Otherwise, the CPLEX would tend to choose the equipment with longer life.

Table 2: Parameters regarding depreciation costs for trucks

	Truck											
	Type 1			Type 2			Type 3			Type 4		
Model	M1	M2	M3	M1	M2	M3	M1	M2	M3	M1	M2	M3
Depreciation (%)	25	28	33	28	33	33	25	33	33	25	28	30
Life (in years)	8	7	6	7	6	6	8	6	6	8	7	6
Capacity (tonne)	100	120	180	120	150	200	80	160	200	80	140	175
Capital cost (\$M)	1.0	1.2	1.5	1.25	1.35	1.75	0.85	1.4	1.6	0.75	1.3	1.5
Operating hours (hK/year)	4.5	4.9	4.2	4.65	4.8	4.35	5.1	4.8	5.2	3.85	4.4	4.6
Distribution W: Weibull E: Exponential	W	W	W	E	E	E	E	E	E	W	W	W
Distribution parameters	(α, β) 2.82 5.40	(α, β) 2.25 4.90	(α, β) 2.44 5.06	(λ, γ) 0.34 1.23	(λ, γ) 0.58 1.96	(λ, γ) 0.27 2.15	(λ, γ) 0.34 2.28	(λ, γ) 0.25 2.25	(λ, γ) 0.52 2.88	(α, β) 2.72 5.45	(α, β) 2.23 5.16	(α, β) 2.88 5.19
Preventive maintenance cost	$35251 * R(t) - 1.705$	$32452 * R(t) - 1.670$	$29564 * R(t) - 1.896$	$38509 * R(t) - 1.888$	$38947 * R(t) - 1.790$	$39569 * R(t) - 1.912$	$27522 * R(t) - 1.674$	$35659 * R(t) - 1.834$	$37908 * R(t) - 1.892$	$33865 * R(t) - 1.865$	$34869 * R(t) - 1.943$	$36879 * R(t) - 1.754$
Total operating cost (\$/h)	154.5	167.7	190.4	167.3	175.4	179.7	153.6	170.2	186.4	156.9	172.8	186.2

Table 3: Parameters regarding depreciation costs for loaders

	Loader								
	Type 1			Type 2			Type 3		
Model	M1	M2	M3	M1	M2	M3	M1	M2	M3
Depreciation (%)	33	33	28	28	33	25	33	26	28
Life (in years)	6	6	7	7	6	8	6	8	7
Capacity (m ³)	40	75	80	60	80	90	60	80	90
Capital cost (\$M)	1.6	2.5	2.8	1.9	3.0	3.8	2.1	2.9	4.0
Operating hours (hK/year)	5.8	5.4	5.5	5.75	5.8	6.0	5.85	5.7	5.9
Distribution W: Weibull E: Exponential	W	W	W	W	W	W	E	E	E
Distribution parameters	(α, β) 1.89 3.33	(α, β) 2.13 2.77	(α, β) 2.29 3.28	(α, β) 2.44 3.67	(α, β) 2.51 2.55	(α, β) 1.95 3.75	(λ, γ) 1.06 3.51	(λ, γ) 1.01 3.22	(λ, γ) 1.12 2.97
Preventive maintenance cost	$11153 * R(t) - 2.345$	$12342 * R(t) - 2.373$	$12239 * R(t) - 2.406$	$11954 * R(t) - 2.289$	$11867 * R(t) - 2.265$	$12345 * R(t) - 2.321$	$9456 * R(t) - 2.489$	$10912 * R(t) - 2.505$	$10234 * R(t) - 2.517$
Total operating cost (\$/h)	342.3	389.5	412.5	312.7	367.9	405.7	342.4	390.7	443.2

Preventive maintenance costs are computed in terms of the equipment reliability analysis. Using historical failure data on equipment, a distribution is fitted into the data. The distribution parameters for the equipment are also given in Tables 2 and 3. Weibull or exponential models are at most fitted as reliability models. For one truck (Type 1 – 100 t) and one loader (Type 1 – 40 m³), the distributions fitted to equipment failure are shown in Figures 4 and 5. Using regression, the power models are established to show the cost and reliability relationship. Reliability is the dependent variable. Thus, for each period, a preventive maintenance cost is calculated from the reliabilities. For example, in the second period, truck reliability is found from the parameters given in Table 2. The reliability is calculated as 94%. Using the formulae $(35251 * R(t))^{-1.705}$ where $R(t)$ is fractional value), preventive maintenance cost is calculated as \$39,173.15. However, in the

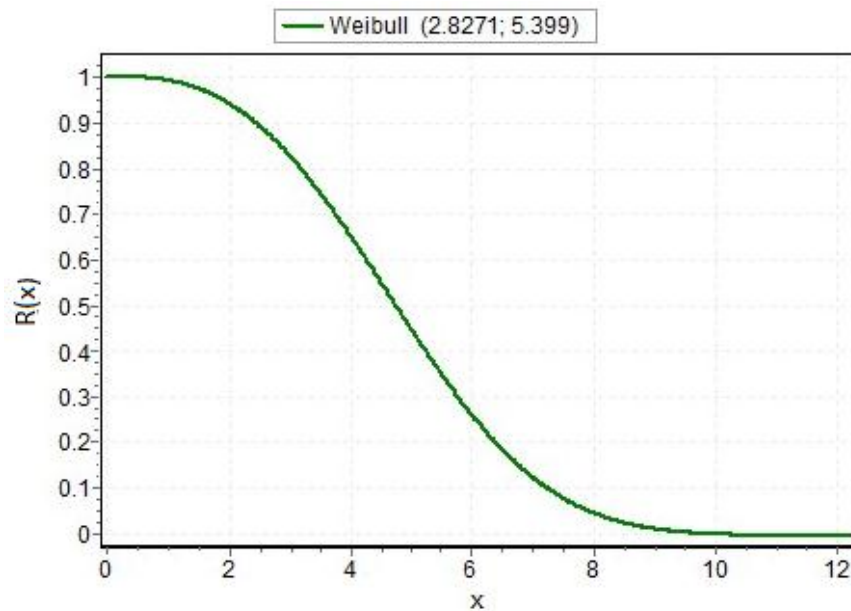


Figure 4: Reliability function of truck type 1

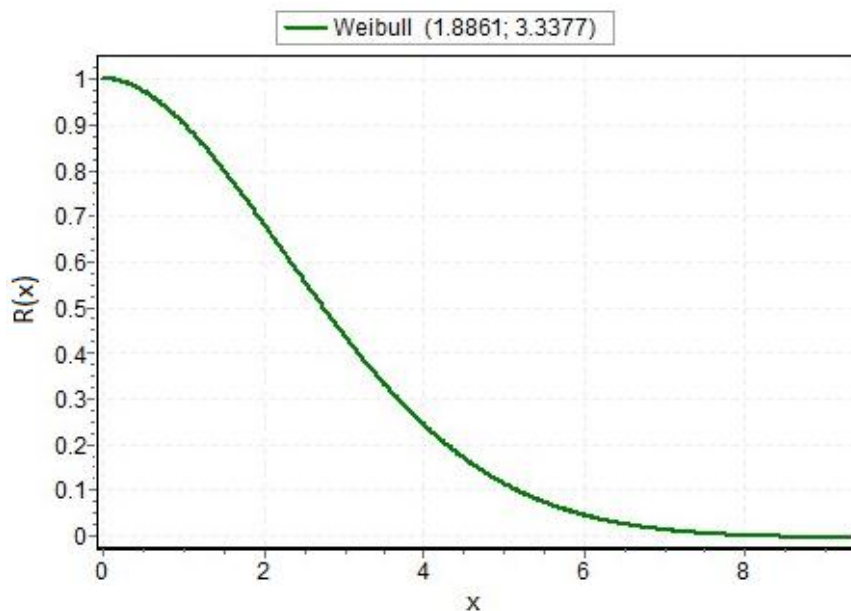


Figure 5: Reliability function of loader type 1

sixth year, the reliability is 26% and the preventive maintenance cost is \$350,463. For some equipment, this cost can be very large as the periods approach the end of the equipment's life.

To calculate equipment operation costs, the Cobb-Douglas cost function considering the economies of scale is first used. The value found is constrained to the operation cost of the equipment configuration selected. The reason why the Cobb-Douglas cost function is not sufficient arises from difficulties in the calculation of the coefficients. This cost function does not also consider multi-period character of equipment selection. Since a firm extracting only gold is considered in the case study, there are no economies of scope.

Using CPLEX, optimal results are solved in approximately 32 hours. Figure 6 shows some cross-sections of block sequencing. In Table 4 and Figure 7, the numbers of blocks to be extracted with respect to destinations to be sent are given. As can be seen, the capacity utilization is quite acceptable. The capacity utilization is important because the opportunity cost emerging from the utilization is not regarded in the cost structure of the optimization model; the opportunity cost is not a direct cost. Table 5 and Figure 8 summarizes average grade in each destination according to periods. Average grades of periods are descending order. This is a simple result stemming from the fact that the objective function that is maximizing the NPV; in this objective, the valuable blocks are forced to extract in earlier periods as long as blocks are accessible because opportunity cost increases by time. Varying ore quality in terms of periods introduces extra difficulties for mineral processing operation. It is expected that the effect resulting from input ore variation in mineral processing can be handled by changing some design parameters such as operation time or reagent quantity.

The project NPV is \$1,840,165,068 in total. The sequencing without cut-offs allows more configurations. For example, there are chances that an intermediate grade block may be sent to high-grade process or waste dump. Hence, strict capacities can be met such that the NPV increases. Quicker accessibility may be allowed into high-grade areas. In multi-process cases especially, this provides an opportunity to generate more NPV.

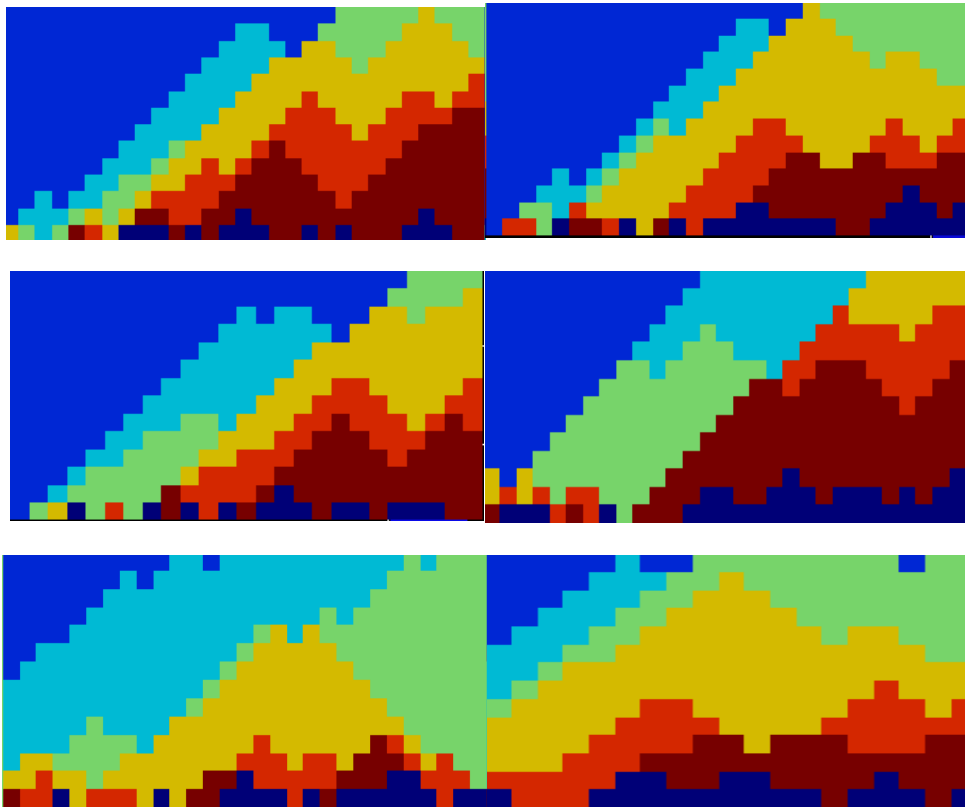


Figure 6: Some cross-sections from the schedule generated

Table 4: The number of blocks to be extracted

	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
Waste Dump	2198	2170	2102	2057	2087	2065
Process 1	976	952	899	878	864	841
Process 2	482	473	464	437	412	403

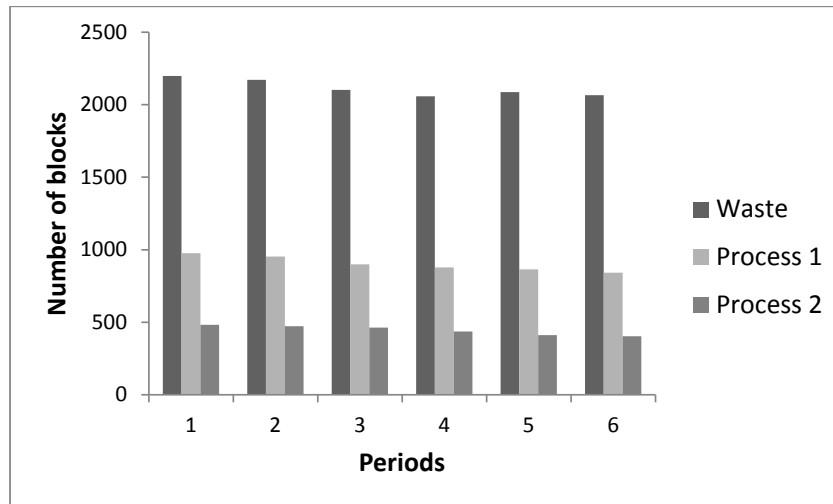


Figure 7: The number of blocks to be sent in destinations in terms of periods

The selected equipment is summarized in Table 6. The total quantity of material to be extracted for first year is 2198 waste blocks + 976 low grade process blocks + 482 high grade process (3656 in total). Given 5000 tonne blocks, the total material quantity is 18,280,000 tonnes in the first year. The total transportation capacity of selected equipment is 18,826,000 tonnes/year for trucks and 9,708,000 m³/year for loader. Given that the specific gravity of the run-of-mine material is approximately 1.90 tonnes/m³, quite reasonable matching is obtained. The specific gravity of in-situ material is 2.15 tonnes/m³. Table 7 gives a summary of the equipment matching. This matching should be also satisfied in short term via a dispatching management.

5 Conclusions

Block sequencing, ore-waste discrimination and equipment selection/allocation are simultaneously solved in this paper for the given capacities. The mathematical formulation developed herein makes the decisions on when to extract mining blocks, where to send these blocks and with which equipment. The proposed approach and corresponding mathematical programming formulation approaches equipment selection and allocation as part of long-term planning. A case study conducted using data from a gold mine demonstrates the pros and cons of the proposed approach, which includes a more comprehensive cost structure that integrates reliability, maintenance, depreciation and econometric modelling. As a result a more realistic schedule can be generated.

Table 5: Average grade of material to be extracted (g/tonne)

	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
Waste Dump	0.41	0.35	0.28	0.23	0.18	0.14
Process 1	3.29	2.93	2.71	2.45	2.34	2.21
Process 2	15.34	14.34	13.45	9.53	6.43	4.23

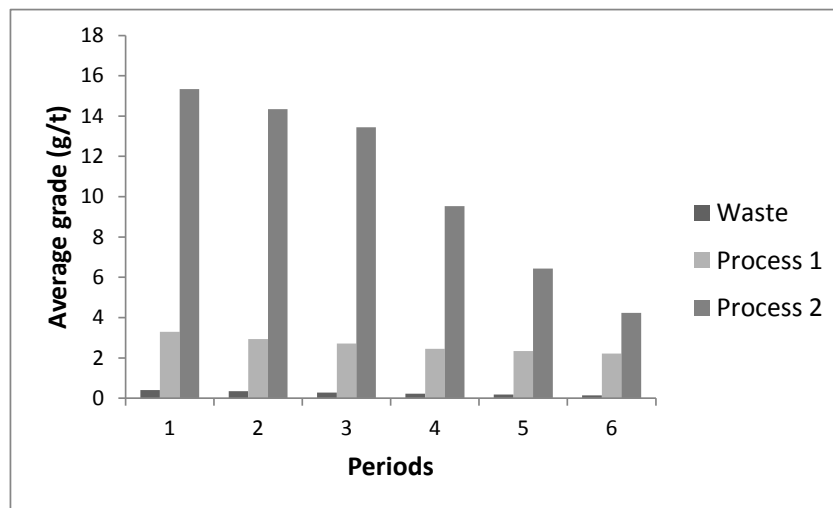


Figure 8: Average grade of material in destinations in terms of periods

Table 6: Selected fleet

Truck	Type 3 (80 t)	Type 4 (175 t)	Type 1 (120 t)
Number	6	5	5
Annual capacity (t)	4896000	8050000	5880000
Cycle (min)	30	30	30

Loader	Type 1 (40 m ³)	Type 2 (60 m ³)
Number	3	2
Annual capacity (m³)	5568000	4140000
Cycle (min)	7.5	10

Table 7: Summary of equipment matching

		Trucks		
		Type 3 (80 t)	Type 4 (175 t)	Type 1 (120 t)
Loaders	Type 1 (40 m ³)	x		x
	Type 2 (60 m ³)		x	

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