Selection of waste dump sites using a tabu search algorithm

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Synopsis

The selection of optimal site(s) for waste dumps is a significant problem of surface mines. A number of financial, environmental and safety requirements must be simultaneously considered to avoid potential losses. In this paper, the site selection problem is solved by the so-called tabu search, which is a local or neighborhood search procedure moving iteratively from one possible solution to another until a predefined stopping criterion is met. The application of the method requires a preliminary qualitative analysis for the selection of possible locations given environmental considerations and safety requirements. The method then focuses on minimization of dump and roadways construction and transportation costs such that dump capacities and blending requirements will not be exceeded. Some model data such as sulphur and nitrogen contents of each waste material are treated as random data, and chance constrained programming, a stochastic programming approach, is used to deal with the random characteristics of these data. The method proposed is demonstrated for six neighbouring mines varying extraction rates of wastes and five possible dumps varying with construction costs. The results show that tabu search is a very effective method in selecting optimal sites of mine waste dumps.

Keywords: mine wastes, site selection, chance constrained programming, tabu search

Introduction

Open pit operations remove large volumes of waste in order to expose ore. This waste material, that is low content or barren material, is then disposed to into dump(s)[1–6]. Waste management is an integral part of production planning because material-handling cost is almost half of the mining costs[7,8]. When the mining operation is completed, mined area and waste dumps are rehabilitated. Location analysis as a part of rehabilitation planning is considered prior to the beginning of mining operations. The selection of a dump site is a complex engineering problem involving financial, environmental and safety considerations. Financial considerations comprise the costs of establishing dump, roadway construction, waste material transportation and site rehabilitation. These costs are affected by many factors, for example, topographic and ground conditions, reclamation, replanting and restoring characteristics, elevation between mine and dump, material properties and quality of roads. Environmental considerations include the possibility of acid generation and reactivity, drainage requirement determined by analysis of groundwater discharge areas, the effects on biotypes, the existence of physical contamination of ground water by waste weathering, and the protection measures for the surrounding environment from contaminants by reclamation upgrading the physical character of mine waste dumps. Safety considerations require geotechnical failure and structural stability analysis because the dump must be designed in such a way as to minimize erosion, migration of contaminants into environment and other failure possibilities.

When a site meeting environmental requirements is selected, construction costs are incurred to prepare the waste dump. If a problem emerges after the waste dumping operations begin, relocation may be impossible due to high costs. The dump capacity should accommodate the amount of waste material to be extracted. Depending upon the type of material and fracture frequency, *in situ* material swells from 10 to 60% when mined. Loose material will compact to some degree after dumping. All amounts of materials considered in the present paper are the swelled and compacted materials.

Many mining problems such as site selection, production scheduling, ultimate pit contour determination, cut-off grade optimization and equipment selection are combinatorial optimization problems where the set of feasible solutions is discrete and the goal is to find the best possible solution. Some operations research methods were devoted to

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the problem of optimal site selection for dumping[9,10]. Intelligent search methods, known as metaheuristic, have been also developed for solving this class of computational problems in an efficient way, and several new techniques have been developed in last three decades; for instance, tabu search, neural networks, simulated annealing, genetic algorithms, memetic algorithm and ant colony techniques. The tabu search technique introduced by Glover[11,12] is used here to handle the problem of selecting waste dump sites and determining the amount of material to be dumped to the selected sites. This problem is very well suited for solving by tabu search especially, as problem size and model features such as nonlinearity, the standard solution techniques may not be used. In these cases, metaheuristics such as tabu search can play an important role in solving the mining problems given above.

In the next sections the problem of finding possible dump site(s) at minimum cost while satisfying environmental, safety and financial requirements is first formulated as a mathematical programming model. Then, a solution strategy based on tabu search is adapted to this non-linear optimization problem. Subsequently, a case study demonstrates the proposed approach of selecting waste sites in a region with six coal mines. More specifically, the proposed approach is applied to selecting the number of dumps and amount of material to be disposed in each dump, while maintaining desired levels of contaminants, such as sulphur and nitrogen, and complying with dump capacities constraints.

Problem formulation

Given m possible dump sites and waste material extracted in n mines, select the dump site(s) to dispose all waste material in such a way as to minimize total costs of (a) constructions of the site(s) and roadways; and (b) material transportation. The objective function, $F(x, b)$, can be decomposed into two sub-problems:

- ➤ The locations of dumps to be constructed are determined (right side of Equation [1])
- ➤ The allocation, the amount of material to be sent to each constructed dump, is determined (left side of Equation [1]).

In operational research terminology, this problem is known as capacitated facility location problem[13,14]. Notation and formulation follow

Indices:

- i mine
- j dump
- f element

Parameters:

- n the number of mines from which waste material is extracted
- m the number of possible dumps
- p total number of elements considered

Data:

- c_{ij} transportation cost of waste material from mine i to dump j
- t_j cost of dump j and its roadway construction
- A_i the amount of waste material extracted from mine i annually (m^3/year)
- P_j the capacity of dump site j (m^3/year)
- g_{fi} average content of material extracted for element f in mine i
- G_f maximum allowable content for element f in any dump.

Variables:

- x_{ij} the amount of waste material to be transported from mine i to dump j
- b_j a binary variable since the dump j is either established (b_j=1), in which case the fixed construction costs t_j are incurred, or not established (b_j = 0)

$$b_j = \begin{cases} 1 & \text{if dump } j \text{ is constructed} \\ 0 & \text{otherwise} \end{cases}$$

Formulation:

$$\text{Minimize } F(x,b) = \sum_{i=1}^{n}\sum_{j=1}^{m} c_{ij}x_{ij} + \sum_{j=1}^{m} t_j b_j \qquad [1]$$

$$\text{Subject to } \sum_{j=1}^{m} x_{ij} = A_i \quad i = 1,\ldots,n \qquad [2]$$

$$\sum_{i=1}^{n} x_{ij} \le P_j b_j \quad j = 1,\ldots,m \qquad [3]$$

$$\sum_{i=1}^{n} g_{fi}x_{ij} - G_f\left(\sum_{i=1}^{n} x_{ij}\right) \le 0 \quad j = 1,\ldots,m \quad f = 1,\ldots p \qquad [4]$$

$$x_{ij} \ge 0 \ \forall_i \text{ and } \forall_j \qquad [5]$$

Solution strategy

A naïve approach to solve a combinatorial optimization problem is to list all the feasible solutions of the problem. This approach is called complete enumeration and becomes inefficient as problem size increases. Tabu search begins with an initial solution, which is an assignment of values to decision variables, and assesses the objective function for this solution. Then, the neighbourhood is constructed to identify adjacent solutions that can be reached from any current solution by a simple operation. A subset of candidate feasible solutions is generated from the current feasible solution. If the best of these moves is not tabu or if the best is tabu but meet the aspiration criterion, this move is selected as the new current solution. Tabu list comprises the solutions that have been visited in the recent past. If a solution is excellent quality and has not yet been visited, this solution, which is better than the currently best known solution, is allowed by a commonly used aspiration criterion. The procedure is repeated for a certain number of iterations. When the procedure is terminated, the best solution obtained so far is accepted as the solution.

The size of the search neighbourhood, nsize, has a significant influence on the result of the technique: the larger the search neighborhood, the better the quality of the solution. However, a larger nsize requires more execution time. The maximum number of consecutive non-improving iterations is used to terminate the technique. The higher value of the maximum number of non-improving iterations, ITER, the better the quality of the solution.

A tabu search algorithm contains three main strategies: forbidding strategy, freeing strategy and stopping criterion[15,16]. The forbidding strategy is operated to avoid cycling problem by forbidding certain moves. In other words, the main mechanism for exploiting memory in a tabu search is to classify a subset of the moves in a neighborhood as forbidden or tabu. The rule to avoid the cycling does not visit the solutions already visited during the last tabu list size (*TL*) of iterations. The selection of an appropriate value of *TL* has a direct influence of the performance of the technique. If the value is too small, the probability of cycling is high. A small *TL* emphasizes intensification, which the search may allow to be reversed after a few iterations. If it is too large, the search might be driven away from good solution regions before these regions are completely explored. A large *TL* emphasizes diversification, whose reversal may be very difficult. If tabu restrictions, which are certain conditions imposed on moves that make some of them forbidden, are met, a solution is acceptable. However, a solution can also be accepted if an aspirations criterion is met. The aspiration criterion is the rule that overrides tabu restrictions. If a certain move is forbidden by tabu restrictions, when satisfied, aspiration criterion can make this move allowable. The freeing strategy controls whether a solution is in tabu list or not. The strategy deletes the tabu restrictions of the solutions so as to reconsider in further steps of the search. An accepted solution remains on the tabu list for *TL* iterations. When a specified number of iterations are performed, the stopping criterion terminates the tabu search procedure.

The proposed tabu search algorithm for dump site selection is described as follows:

➤ *Step 1*—Initiate parameters; the size of neighbourhood, *nsize*, the size of tabu list, *TL*, the maximum number of non-improving iterations, ITER. An initial solution, y, is introduced and its cost is calculated, *tcost*(y).
Set: $y_{current} = y, y_{min} = y, y_{best} = y$
TL = 0
BV = *tcost*(y) where *BV* is the best value obtained so far
k = 1
min = ∞

➤ *Step 2*—Generate *nsize* random solution from $y_{current}$. For each solution, the cost is calculated. The solution with minimum total cost is selected as y_{min}.
Set: *do i* = 1,*nsize*
derive y_i from $y_{current}$ such that the constraints are not violated using perturbation mechanism and calculate $tcost(y_i)$
enddo
arrange solutions in ascending order from $tcost_{min}$ to $tcost_{max}$
$BV = tcost_{min}$
if ($tcost_{min}.lt.min$) then
$min = tcost_{min}$
$y_{best} = y_{min}$
endif
$l = 0$

➤ *Step 3*—Check if the selected solutions are in tabu list or satisfy the aspiration criterion.
Set: $l = l + 1$
If (($y_l \notin TL$).or.(($y_l \in TL.and.BV < min$)) then
$Y_{curent} = y_l$
make $y_{current} \in TL$
$k = k+1$
go to step 4
otherwise
if (l.eq.*nsize*) go to step 2
$l = l + 1$ and go to the beginning of step 3
endif

➤ *Step 4*—Check whether or not the stopping criterion is satisfied.
If (*k*.eq.*ITER*) report *ybest* and *tcostbest* and terminate the program otherwise go to step 2.

Due to fluctuations in the contents of elements under consideration, model variables such as sulphur and nitrogen are treated as random variables. Therefore, a reliability criterion is required. CCP is used to tackle with the random nature of the variables in the model constraints[17,18].

The CCP comprises 'chance constraints', which incorporate a strict measure of the probability with which the constraints must be met. For example, the chance constraints of the Equation [4] for attribute *f* (say, for example, sulphur content) of waste material may be specified as:

$$P\left[\sum_{i=1}^{n} g_{1i} x_{ij} - G_1\left(\sum_{i=1}^{n} x_{ij}\right) \le 0\right] \ge \alpha_1 \quad j = 1,\ldots,m \qquad [6]$$

where α_1 is the reliability or risk level of the constraint on attribute *f* and *P* is the probability. Generically, the objective is to calculate how much in waste material should be dumped such a way as to satisfy environmental requirements within the specified reliability level. The chance constraints are transformed into appropriate deterministic equivalents yielded from the vector of the random variables for characteristics of each mine.

Assuming normality of each attribute of waste material to be dumped, the resulting deterministic equivalent of Equation [6] is

$$m_i^T x + k_{\alpha i}\left(x^T V_i x\right)^{0.5} - G_f \le 0 \quad i = 1,\ldots,n \qquad [7]$$

where:

$$m_i^T = E\left[\tilde{g}_i^T\right] \qquad [8]$$

$$E\left[\frac{\sum_{i=1}^{n} g_i x_{ij}}{\sum_{i=1}^{n} x_{ij}}\right] = m_i^T x \quad j = 1,\ldots,m \qquad [9]$$

$$Var\left[\frac{\sum_{i=1}^{n} g_i x_{ij}}{\sum_{i=1}^{n} x_{ij}}\right] = x^T V_i x \quad j = 1,\ldots,m \qquad [10]$$

$$\Phi(z) = \int_{-\infty}^{z} \phi(t)\, dt \qquad [11]$$

$$\phi(t) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{1}{2}t^2\right) \qquad [12]$$

$$k_{\alpha i} = \Phi^{-1}(\alpha_i) \qquad [13]$$

V_i is the variance-covariance matrix for random element g_i in constraint *f*. We also assume random vectors $\tilde{g}_i^T$ are statistically independent. The problem is now a non-linear programming problem.

Case study

To demonstrate site selection for mine wastes by the proposed tabu search algorithm, a case study is presented in this section. In a coal region, there are six mines. Five possible dump sites are determined on the basis of qualitative analysis relying on only environmental concerns. The problem is to determine the number of dumps and the amount of material to be disposed such that the sulphur and nitrogen contents of each selected dump do not exceed pre-defined limits given a dump capacity constraint. High sulphur and nitrogen contents of waste material can lead to acidic water generation, which may be harmful to soil, river systems and farmland. Therefore, these contents should be controlled to avoid possible environmental deterioration.

The parameters used in the tabu search algorithm for site selection of mine waste disposal are given in Table I. An initial solution was generated by placing randomly the some amount of material in the mine-dump matrix (Table II). For example, the waste material to be extracted from the Mine 1 (891458 m^3) is disposed of Dump 2 and so on. The cost value of this solution ($9 070 269) is calculated from the objective function using the coefficients in Table I. This solution is perturbed five times, which are the size of neighbourhood, by the mechanism as follows:

- ➤ *Step 1*—Two integer random numbers (α and β) are drawn such that $\alpha \in \{1,\ldots, NM\}$ and $\beta \in \{1,\ldots,ND\}$ to determine which mine-dump route ($k_{\alpha\beta}$) will be perturbed
- ➤ *Step 2*—Another pair of integer random numbers (δ and ϕ) is generated to determine the new destination(s) to which waste material is to be moved.
- ➤ *Step 3*—Another random number (τ) is drawn between [0, 1] to determine the amount of waste material to be moved to new destination(s). τ is multiplied by the amount of material to be sent from Mine α to Dump δ and this amount is subtracted from $w_{\alpha\phi}$.

As long as the constraints are not violated, the solution is accepted. Otherwise, Steps 1 to 3 are repeated. This procedure is repeated until five feasible solutions are obained. These five cost values are arranged in ascending order. Starting from the best solution, if there is no violation in the tabu list or if the cost value of the solution under consideration satisfies the aspiration criterion, this feasible solution is accepted as current solution. Otherwise, go to the other feasible solution in the order. The feasible solution yielding minimum cost is accepted as the current solution. This solution is now in the tabu list for three iterations. This solution is stored as the best solution obtained so far. These steps are repeated until the stopping criterion is satisfied. Then, the best solution is recorded and the program is terminated. In Table III, the solution obtained at the end of program is given. The cost value of the best solution is $5 571 217. As expressed in the parameter file, the content criterion should not exceed 0.5%. The sulphur and nitrogen contents of the selected dumps (Dumps 2 and 4) are 0.4998467% and 0.4980784% for sulphur and, 0.3185989% and 0.3499957% for nitrogen, respectively. Dumps 2 and 4

Table II

Initial feasible solution

	Dump 1	Dump 2	Dump 3	Dump 4	Dump 5
Mine 1		891458	608542		
Mine 2		1592836	507164		
Mine 3			1900000		
Mine 4		1754362	745638		
Mine 5		1476203	923797		
Mine 6		723929	976071		

Table I

Parameter file

2850	Number of iterations (ITER)
5	Number of candidate solutions (nsize)
3	The size of tabu list (TL)
6	Number of facilities (NM)
5	Number of possible dumps (ND)
2	A parameter used in perturbation
2	Number of attributes (sulphur and nitrogen)
0.50 0.35	Maximum allowable sulphur and nitrogen
5900000. 5800000. 7500000. 6600000. 7300000.	Capacity of each dump
1500000. 2100000. 1900000. 2500000. 2400000. 1700000	The amount of waste
0.72 0.33 0.36 0.45 0.40 0.53	Sulphur content of each waste material
0.20 0.16 0.13 0.32 0.23 0.36	Nitrogen content of each waste material
1.2816 1.2816	Probability level for chance const. prog. both sulphur and nitrogen
0.05 0.04 0.11 0.05 0.08 0.10	Standard deviations for sulphur
0.15 0.12 0.16 0.14 0.20 0.12	Standard deviations for nitrogen
08.59 03.67 13.34 03.45 11.27	Distance matrix
06.54 03.50 10.09 05.38 13.59	
11.40 06.06 15.18 02.87 08.42	
12.98 07.07 16.49 02.82 07.20	
16.38 11.56 20.11 07.81 16.38	
03.54 03.71 08.72 08.24 17.54	
1.1 1.3 1.4 1.4 2.4	Topography factor
1.3 1.5 1.4 1.5 2.6	
2.9 1.8 1.5 1.4 2.2	
2.5 1.5 1.1 1.3 1.0	
1.7 2.7 2.8 2.9 1.0	
1.1 1.2 1.8 1.7 3.1	
0.06 0.11 0.05 0.10 0.15	Cost ($/km)
0.05 0.06 0.04 0.10 0.16	
0.07 0.07 0.04 0.08 0.14	
0.06 0.07 0.06 0.07 0.12	
0.07 0.08 0.08 0.07 0.12	
0.08 0.10 0.06 0.11 0.16	
640000. 850000. 525000. 580000. 735000.	Construction costs of dumps ($)
1.30	Swelling factor

contain 5 516 617 m^3 and 6 583 383 m^3 of waste material.

There is no clear rule for the selection of control parameters, namely the size of neighbourhood, the size of tabu list and the maximum number of non-improving iterations. Therefore, the parameters were determined by experimentation. Cost values versus maximum number of iterations are given in Figure 1, which shows that cost value decreases swiftly and then converges around 2 850 iterations. As seen in Figure 2, the tabu search algorithm was implemented for various neighbourhood sizes. Five is noted as the optimal neighbourhood size because no improvement was observed for *nsize* greater than 5.

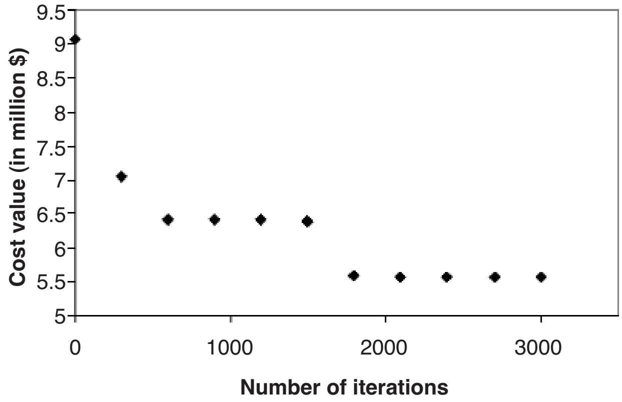

Figure 1—Relationship between the number of iterations and cost value

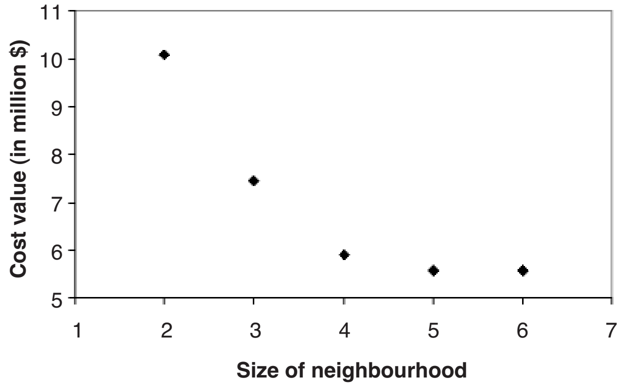

Figure 2—Evolution of the size of neighbourhood versus cost value

Conclusions

Challenging costs and increasing environmental sensitivity demand careful site selection for mine wastes. In this research, a tabu search approach was used to determine optimal dump site selection and the amount of material to be hauled to each dump such that capacity and blending constraints were satisfied. As seen from the optimal results given in Table III, Dumps 2 and 4 were selected for waste material disposal. Total cost using these dumps is $5 571 217. Since the selection of control parameters such as the size of the neighbourhood, the size of the tabu list and the maximum number of non-improving iterations is the problem-specific, the tabu search algorithm requires experimentation prior to the tabu search implementation. One may extend the research by using other elements of the tabu search technique such as strategic oscillation and path re-linking. As mining advances, internal dumping can be considered. The mine planning process should be integrated with dump selection and design to reduce high transportation and related costs.

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Table III

The best solution obtained from the tabu search algorithm

	Dump 1	Dump 2	Dump 3	Dump 4	Dump 5
Mine 1		691964		808036	
Mine 2		2100000			
Mine 3		494436		1405564	
Mine 4		336404		2163596	
Mine 5		193813		2206187	
Mine 6		1700000			

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