

Limestone quarry quality optimization for a cement factory in Turkey

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Synopsis

Many factors govern the size and shape of an open pit, and these must be properly understood and used in the short and long-term planning of any open pit and quarrying operation. The importance of each factor will depend on the particular project, but the geology, grade, and localization of mineralization, extent of the deposit, topography, property boundaries, production rates, bench height, pit slopes, road grades, mining costs, and cut-off grades are key elements of open pits. This paper discusses the work done on the above parameters in order to provide an optimal production plan for a limestone quarry and clay deposits that provide raw material for a cement factory in Turkey.

Soke cement factory has 1 400 000 tons of clinker capacity and is located on the western part of Turkey, in the province of Aydın. It is one of the largest facilities in the cement sector in terms of capacity, and it has a large advantage over facilities because the location of the factory was chosen to obtain the raw materials necessary for cement production within very short distances. However, the old reserves that supplied limestone to the factory had been reported to have run out, and therefore new limestone reserves in the same province have been investigated over the years by experienced geologists. From surface samples, high MgO content was reported in the neighbourhood of limestone formations with high dolomatization; hence, other alternatives were taken into consideration. One alternative with better chemical composition had been found 24 km away from the factory, but the haulage cost of limestone was unacceptable for the factory due to high diesel prices in Turkey.

The maximum allowable MgO content in the pre-mix feed to a rotating furnace is 2.5% MgO content in pre-mix from both limestone and clay deposits. The clay deposits belonging to the cement factory have higher MgO content than the limestone deposit, and therefore this quality problem was taken into consideration first, instead of transporting material from 24 km away.

This study gives the details of work done to evaluate both the clay and limestone deposits, statistical analysis performed on core samples taken from drill holes, mathematical modelling for both sites, and most importantly of all, in-pit homogenization work that reduced the pre-mix MgO content. As a result of this study, the profitable limestone quantity has been improved in order to serve the cement factory over a projected 25 additional years without using any material from the close deposit.

Introduction

There has been much research done on computerized open-pit design in an attempt to find the ultimate pit limit that gives the maximum profit. The next step in the hierarchy of mine planning tasks is production scheduling, which must not only conform to both long-range and the short-range mine plans but also must satisfy many practical details[10]. It has become critical to obtain an exploitation schedule for a deposit that optimizes the stripping ratio, meets the requirements of the mineral processing plant, and, most importantly, achieves the highest discounted cash flow within the final pit limit.

The ultimate pit limit problem has been efficiently solved using the Lerchs-Grossmann[11] graph theoretic algorithm or Picard's[14] network flow method. Optimum pit design plays an important role in mine scheduling.

The open-pit mine production scheduling problem can be defined as specifying the sequence in which 'blocks' should be removed from the mine in order to maximize the total discounted profit from the mine subject to a variety of physical and economic constraints. Typically, the constraints relate to the mining extraction sequence, mining/milling/refining capacities, grades of mill feed and concentrates, and various operational requirements such as the minimum pit bottom width[5].

Several approaches to the scheduling problem have appeared in the literature including heuristics by Caccetta[1] *et al.* and Gershon[9], Lagrangian relaxation by Caccetta[1], parametric methods by Dagdelen and Johnson[4], Francois-Bongarcon and Guibal[7], Matheron[12,13] and Whittle[16], dynamic programming techniques by Tolwinski and Underwood[15], mixed integer linear programming by Caccetta *et al.*[2], Dagdelen and Johnson[4] and Gershon[8,9], and the application of artificial intelligence algorithms such as simulated annealing, genetic algorithms by Denby and Schofield[5], and neural networks by

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Denby[6] *et al*. Because of the complexity and size of the problem, all of these approaches suffer from one or more of the following limitations: the approach cannot address most of the constraints that arise; the approach yields only suboptimal solutions and in most cases is lacking a quality measure; and the approach can only handle small problems[3].

In this paper, we have solved a homogenization problem for a cement factory by applying a heuristic method. Two types of material have been using for clinker production, namely, limestone and clay. Apart from the literature on mine scheduling given above, optimization of the limestone quarry and clay deposits does not contain much complexity, such as finding the ultimate pit limit and maximizing the discounted cash flow. The only problem that the factory faced was the chemical quality of two raw material mixtures used for clinker production. There is no overburden removal to organize during the life of the mine, and the topography of the limestone deposit has limited the number of alternative excavation push-backs. All planning work in open pit mining is based on quality estimation of the deposit. Then, the modelled quality parameters for each operational level of both the limestone quarry and clay deposit can been used together to calculate the annual production capacities and chemical composition of the pre-mix material needed to maintain problem-free feed for clinker. This paper describes a new computer algorithm, used to define modelling parameters of inverse distance methods, that is widely used for estimation purposes. Accurate modelling and solution of practical mining problems has a significant economic impact.

Study area

The Soke cement factory was established in 1974 by the national cement association of Turkey. The location of the factory played an important role because all the necessary raw materials for cement production could be obtained over very short distances. Limestone is the main raw material for cement production and comes from a deposit located 2 km away from the factory, with two clay deposits located 4 km away. This feature of the deposits has kept the main transportation costs at a minimum level. The most important parameters of cement production technology is the chemical composition of limestone and clay mixture, called pre-mix, which is the material fed to rotating furnaces. The CaO, SiO_2, Al_2O_3, and Fe_2O_3 content of the limestone plays an important role in clinker phases in the furnace, and therefore, some modules for these chemical components have been developed over the years to control the optimum charge quality. Some examples of these modules used by the relevant cement factory are given in Table I.

In addition to the chemical component affecting the calcinations process, MgO has another important influence on concrete if it is made of high MgO content cement. The allowable limit of MgO content in cement is 4%, so cement containing more than 4% of MgO is difficult to market. MgO content in cement comes both from clay and limestone deposits as a result of their geological origins. In order to keep MgO content below 4% in cement, MgO content should be less than 2.5% in the pre-mix material, or mixture of limestone and clay.

Table I

Modules used by Soke cement factory

Name of the modulus	Formula of the modulus	Value
Lime saturation factor	$CaO/(2.8SiO_2+1.18Al_2O_3+0.65Fe_2O_3)$	0.95
Silica modulus	$SiO_2/(Al_2O_3+Fe_2O_3)$	2.4
Alumuna modulus	Al_2O_3/Fe_2O_3	16

After establishment of the factory, geologists found out that there had been a limited limestone reserve in the area with low MgO content; hence, the factory changed owners twice because of a usable limestone reserve shortage. In 1999, Batisoke bought the factory, and since then, it has been using the limited 'good quality' limestone together with the limestone coming from another deposit 24 km away from the factory. Investigative work on the exploration of new deposits had been in progress until 2001. In the scope of this work, 39 core drillings were performed, and 2 399 samples with 1 m length had been analysed by the factory's chemical laboratory.

After obtaining the results of chemical analysis performed on the core samples, the firm requested modelling and homogenization work in 2004 from the Dokuz Eylul University Mining Engineering Department located near the factory. This paper describes the work done on modelling and the best utilization of limited resources by using short, medium, and long-term production planning techniques. Optimum pit production sequences (those that meet the quality requirements of the cement factory together with the annual production rate) will be introduced later in this paper.

Quality evaluation of deposits

As stated in the previous section, a key component of this study is the MgO percentage. The annual clinker production capacity of the cement factory is 1 000 000 tons/year. To achieve this amount of clinker, it is necessary to mine 1 000 000 tons/year of limestone and 400 000 tons/year of clay due to loss on ignition in the furnace. According to technological requirements, the proportion of the limestone in pre-mix is 60% with the remainder as clay. This gives an example of how it is important to consider both limestone and clay deposits together in order to meet the MgO limitation. A total of 22 holes were drilled, resulting in 675 core samples of 1 metre length from the clay deposit, in order to expose the qualitative distribution of the area. There were a total of 39 drill holes and 2 399 core samples from the limestone deposit. The simple statistical analysis performed on the core samples for the MgO content of both clay and limestone deposits are given in Table II and Table III.

The clay deposit can be divided into two different types of clay in terms of the silica modulus (SM). Clay that has less than 2.4% SM is called 'black clay', whereas it is referred to as 'yellow clay' if the SM value is above 2.4%. Since the black and yellow clays behave chemically differently in the returning furnace during the clinker production process, they are mixed in a one-quarter proportion in the pre-mix. Therefore, 100 000 tons of yellow clay and 300 000 tons of black clay can meet the annual clay requirement of the cement factory.

As seen in both Tables II and III, the overall arithmetical mean for the clay deposit is 5.88 MgO% for black clay and 5.64% MgO for yellow clay. When the limestone deposit is taken into consideration, the MgO mean value becomes

Table II

Simple statistical analysis of limestone deposit according to different MgO content

%MgO	$\bar{X}$	SD	N	%
Whole data	1.92	3.12	2399	100
MgO%	0.696	0.703	1920	80.9
0.0–0.5 (1.region)	0.266	0.108	1171	49.4
0.5–1.0 (2.region)	0.698	0.147	331	13.9
1.0–2.0 (3.region)	1.46	0.30	273	11.5
2.0–3.0 (4. region)	2.45	0.28	167	7.1
MgO%> 3 (5.region)	7.05	4.00	457	19.1

$\bar{X}$: Arithmetical mean, SD : Standard deviation, N : Number of sample, % : percentage within the whole data

Table III

Simple statistical analysis of clay deposit

Content	Black clay (SM < 2.4)			Yellow clay (SM > 2.4)		
	(X)	SD	N	(X)	SD	N
SM	2.04	0.13	475	3.05	0.97	47
% MgO	5.88	1.23	475	5.64	1.24	47

1.92%. Supposing the direct use of all material coming from both open pits without any blending process, the overall weighted MgO% content can be calculated by using the following formula:

(1 000 000 × 1.92 % + 100 000 × 5.64% + 300 000 × 5.88) / 1 400 000 = 3.03

The weighted mean of MgO coming from both clay and limestone deposits reaches 3.03, which is well above the acceptable pre-mix value of 2.5. This figure shows that without a good mine production plan, both reserves have limited availability; in other words, if necessary precautions are not taken, the cement factory may have to find another limestone deposit with low MgO content.

Quality modelling of the limestone deposit

In this section, the first of the work done in modelling the limestone deposit is described in detail. For future use, the limestone deposit is grouped according to MgO% content into different regions (Table IV) and different levels of the pit. To plan the bench levels of the quarry, all data taken from drilled cores have been grouped into 5 m intervals, and the most suitable bench levels have been found, as given in Table V. The idea behind this bench grouping is that during operation, it is not possible to produce the limestone with separate 1 m benches. In the stage of bench establishment blasting, all samples within a given interval become a part of the blasted pile and are removed from the locations at the same time with hydraulic shovels. Therefore, grouped data have been used for the modelling studies.

As seen in Table IV, the distribution of MgO content is not regular within the area, and therefore it becomes difficult to model the limestone body by using geostatistic. The inverse distance method was used for modelling purposes for this project, with a newly developed computer algorithm. In the 3D modelling algorithm, first, the most suitable radius of

Table IV

Statistical analysis of different regions regarding MgO% content

Bench level (m)	$\bar{X}$	SD	N
+450 and over	1.20	1.83	49
440–450	1.29	1.29	62
430–440	2.67	3.46	99
420–430	2.81	3.32	138
410–420	2.04	2.66	184
400–410	1.66	2.38	207
390–400	1.98	2.88	226
380–390	1.83	3.17	276
370–380	1.68	2.70	319
360–370	1.91	3.17	288
350–360	2.04	2.92	212
340–350	1.80	3.76	155
330–340	0.98	2.91	93
320–330	4.63	7.74	40

$\bar{X}$: Arithmetical mean, SD: Standard deviation, N: Number of sample

influence for the deposit was found in the NS, EW, and vertical directions. The well-known formula for the inverse distance method can be given by the following:

$$g_{es} = \sum_{i=1}^{n} \frac{g_i / d_i^m}{1 / d_i^m} \qquad [1]$$

where g_{es} is the point that will be estimated for MgO content by the formula given above, g_i is the known MgO contents of the core samples lying within the radius of influence in all three directions, and m is the power factor of the model. The radii of influence in all three directions, namely, the major (R_1), semi-major (R_2) and minor (R_3) axes, are shown in Figure 1. The axis system could be rotated in three directions with angles of θ_1, θ_2, and θ_3 to find the most suitable model for a certain orebody. The intersection point of all three axes is the point through which we estimate all known core sample values within the search shape given in Figure 1.

In order to optimize modelling parameters that minimize the absolute mean error, the known MgO contents in a certain location given in the data file with three spatial coordinates, are taken out and the same location is estimated by using different modelling parameters. For each different set of modelling parameters, the MgO contents of each core sample within the limestone deposit have been estimated by Formula [1], and the mean variation from the original value gives the success of the model parameter.

The computer algorithm was organized to undertake all possible search radii, R_1, R_2, and R_3, within the limits defined by the user, by changing the θ_1, θ_2, θ_3 axes from 0 to 180 degrees, with a simple loop in the computer program to find the estimation variance showing the model error. In the same loop, the power factor of 'm' can be changed within certain limits with the desired intervals. We tested seven variables altogether by the algorithm, and the average absolute mean errors have been found for each of the tested parameters. The algorithm is organized in such a way that it finds the most suitable model that gives the minimum absolute error. Later, the MgO contents of the limestone quarry were modelled with

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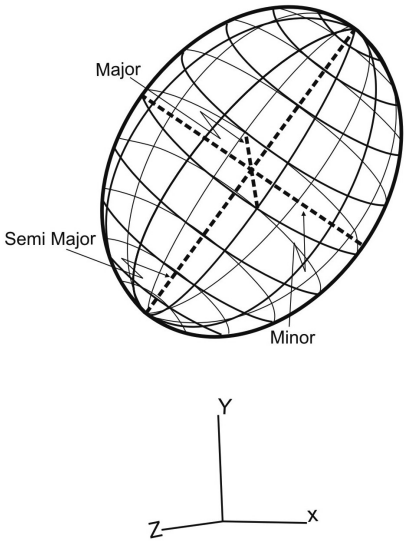


Figure 1—Definition of radius of influence

the parameters that give the minimum estimation error for blocks dimensioned as 25 × 25 × 10 m.

The optimum modelling parameters of the limestone deposit are given below. Cross-validation results give the reliability of the model. The coefficient of correlation for modelling with the parameters given below is 0.84, which is quite satisfactory for such a complex geological structure.

$R_1 = 120$, $R_2 = 410$, $R_3 = 5$, $m = 1.25$, $\theta_1 = 20°$, $\theta_2 = 0°$, $\theta_3 = 0°$.

Quality modelling for the clay deposit

For the clay deposit, two parameters of clay have been taken into consideration in the modelling stages, namely, MgO and the silica modulus (SM). Silica modulus ($SiO_2/(Al_2O_3 + Fe_2O_3)$) divides the clay deposit into two types, black clay and yellow clay. Clay with an SM value of up to 2.4 is called black clay, and above this value it is called yellow clay. The total annual clay requirement of the Soke cement factory is nearly 400 000 tons/year, of which about 100 000 tons/year is yellow clay, with the rest belonging to the black clay group. This classification of clay enables factory technicians to provide a better pre-mix material that will be fed to rotary furnaces. Due to the high MgO content of the limestone, in order to protect any undesired pre-mix composites, clay containing more than 8% MgO will be treated as waste and removed as stripping.

Since the relative regular bedding plane of clay deposit is unlikely in a limestone quarry, a geostatistical method has been applied in the area. The core samples taken with 1 metre intervals have been used for variogram analysis, with the best suited variogram model used for the quality estimation. The main aim in this paper is to explain the homogenization research rather than the modelling strategies, and hence only the necessary parameters used for the block model design are given under this topic. The entire area was divided into 25 m × 25 m × 10 m sized blocks throughout the deposit, and each block was estimated by using the variogram parameters given in Figure 3.

Detailed studies done on the pairs showed that there was no zonal anisotropy in the deposit. Variogram parameters used in the estimation for blocks are as follows:

- Variogram parameters for MgO% content
  Spherical model with nugget effect $h = 110$ m, $C_0 = 5$
  $C = 24$
- Variogram parameters for SM
  Spherical model with nugget effect $h = 185$ m, $C_0 = 0.02$
  $C = 0.12$

Here, h is used as a range that indicates the point beyond which the variogram value remains essentially constant or fluctuates, C_0 is a nugged effect that indicates discontinuity at the origin, and C is the sill of the variogram that shows the maximum γ value

The well-known kriging function has been used for block estimation when the range is less than h,

$$2\gamma = \left(\frac{3h}{2} - \frac{h^3}{l}\right) \quad C + C_0$$

and for values more than h, the block values were calculated by assigning the $2\gamma = C$ function. The γ function model developed for the clay deposit was confirmed by cross-validation, a method of estimating all known data with the γ function and finding the error between modelled and real data. The correlation coefficient for SM between estimations and real values is 0.837, and the same value for MgO is 0.877, which shows that the developed γ function provides reliable and satisfactory results.

Production planning

After obtaining quality distributions of both MgO content and SM for each of the production benches of limestone and clay deposits, the next step was to obtain the optimum short-term production plan that meets the requirements of the cement factory. In order to achieve this objective, the main consideration was to organize annual excavation borders that offer less than 2.5% MgO content in the pre-mix fed to the rotating furnaces. Volume calculations were done by using powerful topographic mapping software. Figure 4 shows limestone production boundaries for the year 2006 as an example. Tables V and VI give the quality of raw material and available amounts for both limestone and clay deposits for the year 2006. The next five-year production plans were prepared annually, and then the rest of the mine plans were drawn for five-year periods. In the process of planning the annual limestone and clay production, no automatic computer algorithms were utilized; they all were created by an AUTOCAD-based mapping program by dividing both limestone quarry and clay deposits into mineable slices. For each period, the annual production that provides an optimum alternative production plan for both the current time period and the future was also examined in order to avoid future bottlenecks.

As shown in Figure 4, the bench +420 is divided into different areas with in terms of MgO content. In the manual optimization process, first, the operational area was divided into blocks by using the 3D estimation method, and then annual limestone quality requirements for MgO were met by considering the clay deposit simultaneously. After satisfying annual production, the process was carried on to optimize it over shorter periods. In Figure 4, the term of the period

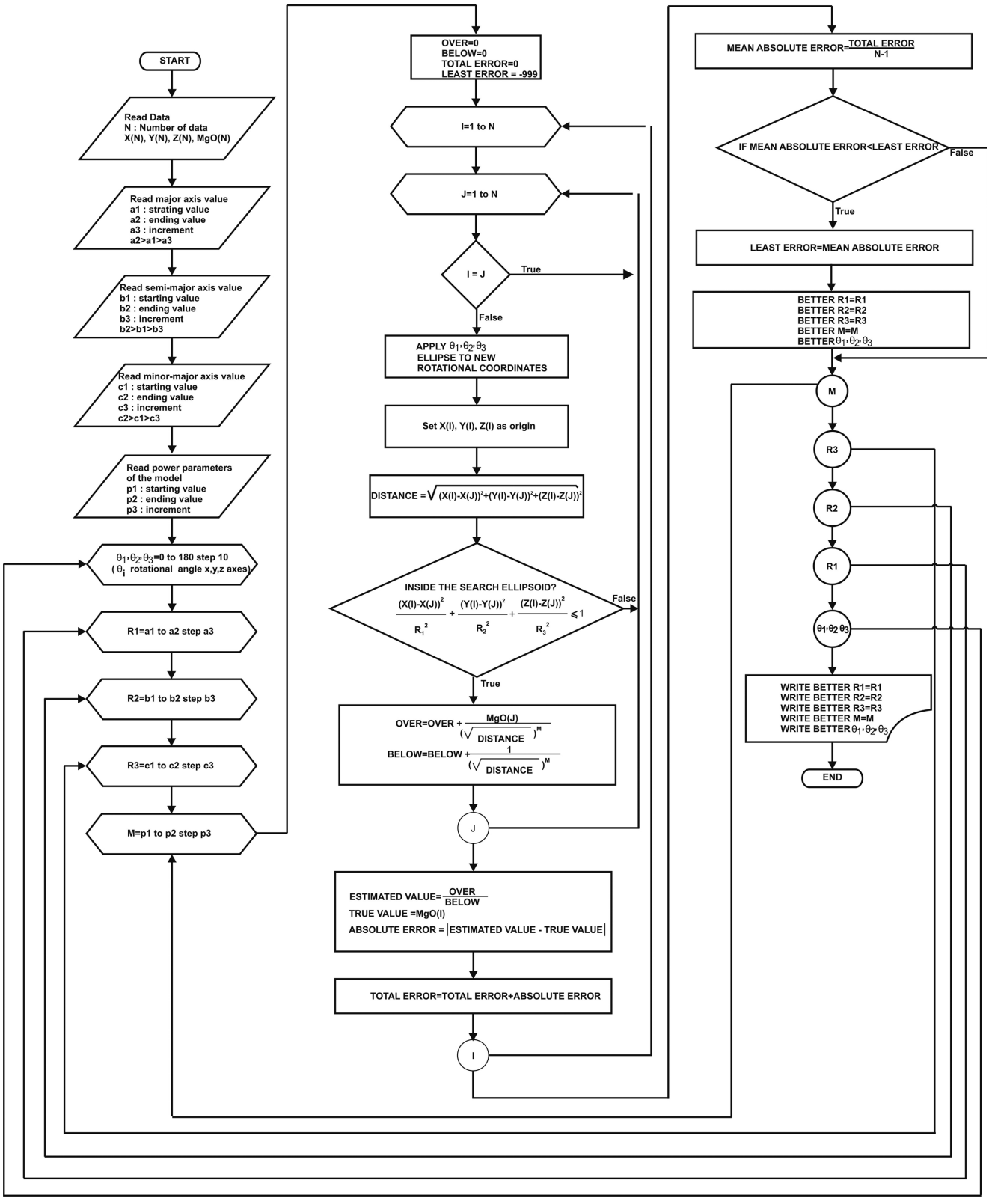


Figure 2—Flow chart of the computer algorithm

shows different months of production. In the production planning stages, details on excavator movement between bench faces, location of the excavator, and requirements for another face excavation were given to provide an optimum MgO strategy.

Both Tables V and VI show how tightly the annual limestone production for MgO content is planned. In 2006, there was a chance to observe the sensitivity of the modelling parameters by collecting data from limestone production blast hole drilling wastes. The results were very promising, but

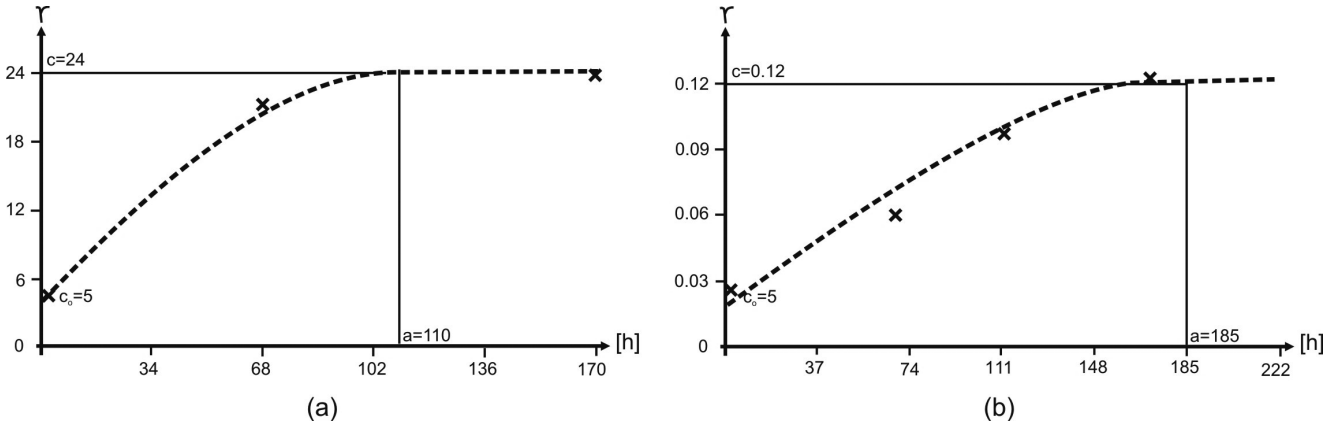


Figure 3—Variogram model for clay deposit. (a) Model for MgO% content (b) Model for SM

strict excavation conditions and an adaptation period for putting the mine production plan maps into practice had prevented us from doing a reasonable sensitivity analysis. The bench coordinates of a certain production period had been given to a mining engineer from the cement factory, and then the topographer had marked the given points to reveal the excavator operations.

Results and discussion

There are several very sophisticated computer software programs available on the market that are capable of doing drill hole interpolations, 3D block modelling, open-pit optimization, and short and long-term production planning. Two important factors limit their widespread usage, such as the costs and complexities needed to understand the modelling and planning modules. They also require at least a basic level of mathematical modelling and estimation technique knowledge. It becomes impractical to benefit from such software if the mine is small and organization parameters are not expected to change very often.

This paper describes a simple and effective method for drill hole interpolation that reduces the risk of misinterpretation of the available data. The method introduced is based on a self-running algorithm that produces the most suitable deposit parameters needed to give a minimum estimation error. If the same work had been done by non-expert people, some problems may occur in the future.

In this study, first, all limestone and clay deposits have been modelled with two different methods, and then an optimum production strategy that provides the maximum utilization for both deposits was given. Nearly 19% of the limestone reserve was treated as waste due to high MgO content before this project, but all the material could be used in cement production if it were excavated in the correct order together with clay deposits. Also, it is important to satisfy factory requirements for the future periods without creating bottlenecks. The maximum utilization of both deposits has

Table V

Bench reserves and quality distribution of material to be excavated for 2006

Bench levels	1. Region	2. Region	3. Region	4. Region	5. Region
+440	262 768	115 430	-	-	134 186
+430	236 482	-	-	-	-
+420	-	-	131 623	115 829	25 317
Total	499 250	115 430	131 623	115 829	159 503

Weighted mean MgO% = (499 250 x 0.25 + 115 430 x 0.75 + 131 623 x 1.5 + 115 829 x 2.5 + 159 503 x 3.5)/1021 635 = 1.23

Table VI

Bench reserves and quality distribution of clay to be excavated for 2006

Bench Levels	Black clay reserve (tons)	SM	Yellow clay MgO%	Reserve (tons)	SM	MgO%
+120	-	-	s-	79 246	3.4	5.0
+110	39 726	2.4	6.7	33 396	2.5	5.0
+100	194 028	2.2	5.9	-	-	
+90	68 746	2.0	4.8	-	-	
Total	**302 500**	**mean**	**5.75**	**112 642**	**mean**	**5.0**

Overall weighted MgO% of pre-mix = (1 021 635 x 1.23 + 302 500 x 5.75 + 112 642 x 5.0)/ 1 436 777 = 2.47

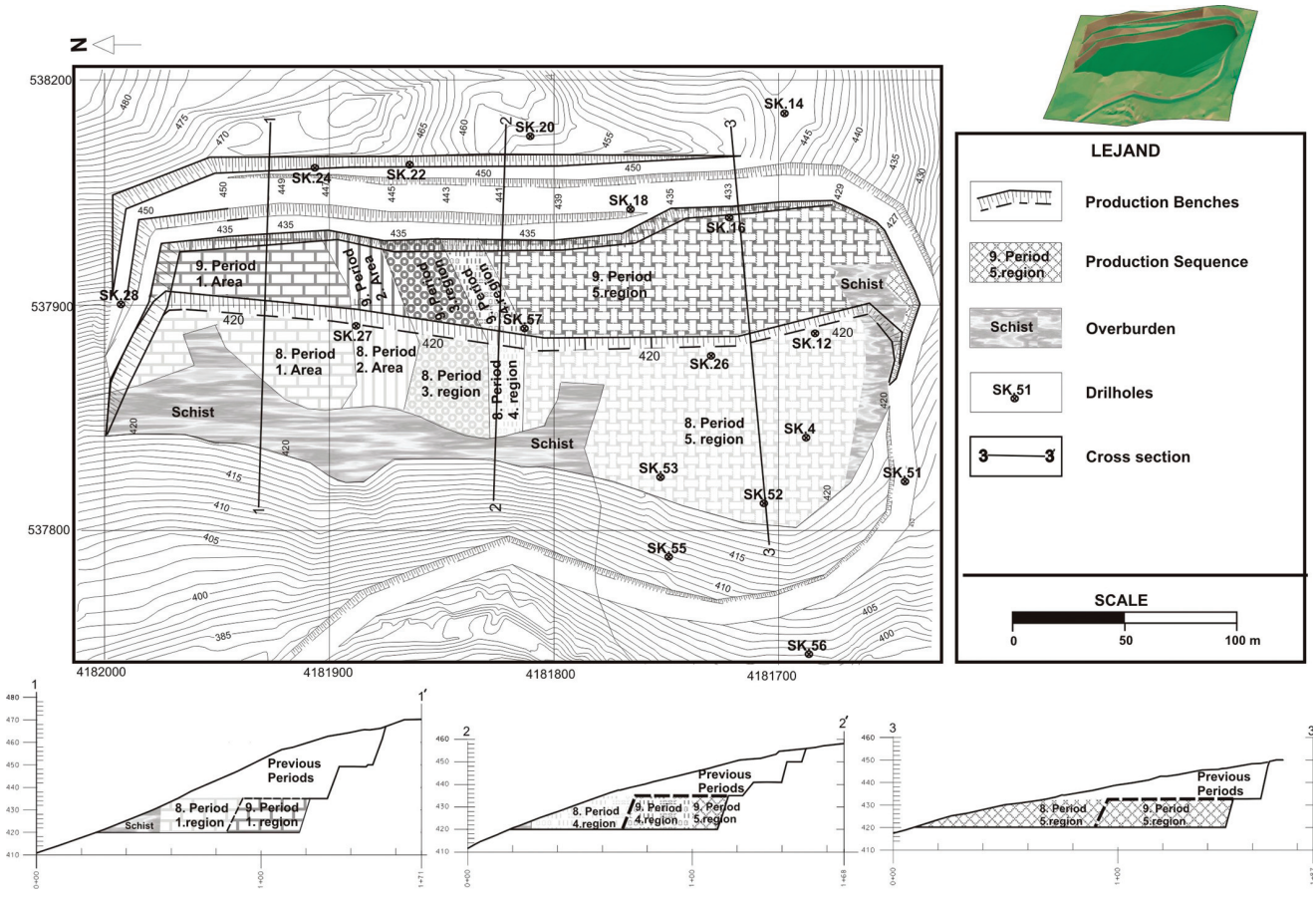


Figure 4—Limestone production plan for the year 2006

been taken as a key factor in this study. This study was completed in the year 2005, and the Batisoke cement factory has been operating the mines under strict adherence to the projects. No problems have been reported thus far by the technical staff of the factory.

After long-term production plans had been completed, 51 829 266 tons of limestone, 16 622 094 tons of black clay, and 3 083 678 tons of yellow clay reserves have been reported; these figures represent the equivalents of nearly 50 years of limestone mine life with the given production capacities.

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