International Journal of Mineral Processing 131 (2014) 31–42

Contents lists available at ScienceDirect

International Journal of Mineral Processing

journal homepage: www.elsevier.com/locate/ijminpro

Choosing a proper sampling interval for the ore feeding a processing plant: A geostatistical solution

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ARTICLE INFO

Article history:
Received 10 February 2014
Received in revised form 3 April 2014
Accepted 7 July 2014
Available online 22 July 2014

Keywords:
In situ variability
Sampling strategies
Geostatistical simulation

ABSTRACT

Estimating the head grades from the ore feeding a processing plant is not a trivial task and is a continuing source of controversy in the mining industry. Grades determined as part of short-term mine planning are frequently not reproduced by sampling the continuous flow of ore at the plant. Head grades are normally obtained by sampling the continuous flow periodically during a day or shift and taking the average of the multiple samples collected. The standard error of this mean grade depends on the ore variability and the frequency (number) of samples. The more samples that are taken, the higher the precision of the calculated mean. Variographic experiments are normally used to map grade variability during a certain period of time, and the extension variance is derived from this variogram. This approach is time-consuming, expensive, and cumbersome, and therefore its use is often avoided in the mining industry. Additionally, a temporal variogram can vary as different ores are mined during the lifetime of the mine. This paper investigates a novel approach based on simulating the grades of orefeeding the processing plant. In situ three-dimensional grade models are constructed using geostatistical simulations. Grade spatial continuity and variability are reproduced in models with the same characteristics of the real deposit. These models are used in mine planning and scheduling, transforming a three-dimensional block model into a one-dimensional string of values feeding the plant (one-dimensional flow). The grades thus obtained have the statistical characteristics of the unknown real grades and can be sampled to simulate a variographic experiment. The results of this study showed consistency and provided satisfactory estimates of the sampling error for various sampling intervals using the simulated grades. They also showed that a variographic experiment can change significantly from time to time as the ore changes and that a selected sampling protocol can become obsolete if not adjusted for ore variability.

Contents

1. Introduction

Discrepancies between the grades obtained by sampling the ore feeding a processing plant and those determined in the mine are a common problem in the mining industry. This so-called mine/mill reconciliation problem has a number of causes (Chieregati et al., 2007). Among

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http://dx.doi.org/10.1016/j.minpro.2014.07.003
0301-7516/

the causes for bias in the grades sampled are: the loss of fine material (which may lead to an underestimation or overestimation of the ore grades), manual sampling (which may lead to particle segregation) and the sampling of insufficient number of increments. In addition to operational causes, many errors are connected with sampling and representativeness. Some of them can be mitigated, but not fundamental errors. The latter cannot be reduced or eliminated even under the most favorable circumstances (Gy, 1998). Thus, at each stage of the sampling protocol, at least fundamental errors are present.

A sample is representative when there is a combination of accuracy and reproducibility. Accuracy is defined as the absence of bias or systematic error. It's a property of the mean, which should be zero. Reproducibility is defined as a low dispersion of the sample values around their mean. It is a property of the variance of the sampling errors, which should be minimal (Gy, 1998). As the mean error and variance of the error are never exactly zero, a sample can be taken as representative when both of these factors are smaller than the respective maximum acceptable values.

One important result of Gy's theory is that the variance of the mean of a lot, when based on several samples, depends on the sampling strategy (Minkkinem and Paakkunainen, 2005). The three possible strategies are:

- systematic selection: can be defined as the selection of points spaced at a uniform time interval. It is the most widely used selection method in the industry.
- stratified random selection: in this method, the total time is divided into uniform intervals, but the points at which samples are extracted are selected at random in each interval. The objective of this method is to avoid possible cyclic fluctuations in the grades of the material.
- completely random sampling: in this method, the samples are extracted on a completely random basis.

In this study, only systematic selection was used. The question asked was: what would be the sampling error (or the difference between the real grades and those obtained using the samples) resulting from extracting a few samples from a continuous flow and declaring the average of these samples to be the grade of the lot? That is exactly what happens when the ore feeding the processing plant is sampled during, for instance, a shift or a day and the average of these samples is declared to be the day/shift grade.

This error, or the difference between what is declared as the grade of a shift (or other period) and the real grade, is simply ignored in many cases. In other mine sites where there is a measure of the error, the result is obtained from so-called variographic experiments. Data obtained during such experiments are used to calculate the error using mathematical techniques based on auxiliary functions and extension variance (Gy, 1998; Grigorieff et al., 2005; Sans and Olzard, 2005; Saunders et al., 1989). The definition of extension variance can be found in Journel and Huijbregts (1978).

Note that it is difficult to obtain data to calculate the error using current methods. As it has been mentioned, these methods are based on a variographic experiment, which needs samples to be taken at short time intervals (such as every 2–4 min) during a period of a few hours to model the influence of the time interval on the mean square difference of the grades (variance). It is difficult to obtain samples for this type of experiment, because to do so requires frequent interruptions to production during the sampling period. Also, the results derived from these experiments are dependent on the type of ore feeding the processing plant at the instant of the test. It is unrealistic to assume that the ore will have similar statistical characteristics over the rest of the mine's lifetime (an extreme assumption) or even the next week.

The results derived from a variographic test will determine the sampling intervals to be adopted, with a calculated error being associated with each time interval chosen. The error associated with extending the value of a few samples to the grade of the entire lot (day or shift) depends on the variability of the ore during the period. Assuming that this ore variability will hold for a long period of time (i.e., stationarity of the variogram over a long time span) might not be realistic.

This paper proposes an alternative approach to the problem of measuring the sampling error (the error due to assuming the grade of shift given samples extracted at every *t* minute interval). The goal here is to use geostatistical methods to predict the mean grade of the deposit and its in situ variability, combined with mine planning (scheduling) to generate possible scenarios for a continuous flow feeding the processing plant. Previous work has used simulated data in an attempt to predict the sampling variance (Rose, 2008), but without considering the issue of reproducibility of the in situ mineral deposit variability.

2. Methodology

The first step in this new sampling methodology is the application of a block simulation model to model ore grade statistics and its space/time connectivity as a continuous flow. A three-dimensional model is constructed, with ore block values reproducing the in situ grade variability and spatial continuity. This model is then applied to mine planning, i.e., pit optimization and mine scheduling. The optimized mine schedule provides a sequence of blocks to feed the processing plant at a given time. The grades of these blocks have previously been determined using geostatistical simulation (Journel and Huijbregts, 1978).

By simulating the entire time series of grades at the plant (which is related to the ore being mined during a given period), it is possible to estimate the error associated with the use of different sampling intervals, and thereby to select a sampling that will lead to an acceptable error for a given ore type.

There are several sources of uncertainty in a mining project, some of which are listed in Fig. 1. At the top left corner of this figure is the long-term block model estimated using kriging and a diamond drill holes dataset. The short-term grade block model is obtained by re-estimating the original long-term block model within certain regions of the deposit (or the entire deposit) after new assays are obtained from blast holes or channel samples. The reconciliation between the grades obtained by these two models measures the efficiency of the estimation methods combined with the quality of the new data incorporated. Next, the grades predicted by the short-term block model are reconciled with the grades declared from sampling the ore feeding the processing plant. This last procedure is the focus of the case study presented in this paper.

These uncertainties cannot be eliminated, but there are alternative approaches to predict and reduce them. One way to quantify the uncertainty arising from a lack of knowledge of the correct mined grade values would be to perform geostatistical simulation. The real mined grades from the mineral deposit are not known, but they can be replaced by multiple equally probable simulated scenarios. These simulated models can be used in mine planning and scheduling to anticipate the uncertainty and risk associated with the grade values during the lifetime of the mine.

This study proposes the use of multiple geostatistical simulated models as the input for planning the mining schedule and for analyzing the sampling uncertainty (the third reconciliation phase in Fig. 1). The steps involved are as follows:

- generation of multiple equally probable three-dimensional (3D) models using the turning bands algorithm (TBA) with conditional data (Journel, 1974);
- mine planning for each grade block model derived from the simulations to obtain the respective mining schedule;
- transformation of the mining sequence from a 3D in situ model to a 1D time series, simulating the feeding of the processing plant;
- simulation of different sampling strategies in the continuous flow;
- calculation of the relative error and the variability of samples within each sampling strategy for the different simulated scenarios for the mineral deposit.