PROACTIVE RECONCILIATION IN MINING INDUSTRY

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ABSTRACT

Reconciliation is the practice of comparing the tonnage and average grade of ore predicted from resource and grade control models with the tonnage and grade generated by the processing plant. The results are usually a group of factors, which are applied to future estimates in an attempt to better predict how the operation may perform. The common practice of reconciliation is based on the definition of the ‘mine call factor’ (MCF) and its application to resource or grade control estimates. The MCF expresses the difference, a ratio or percentage, between the predicted grade and the grade reported by the plant. Therefore, its application allows the correction of block model estimates. This practice is called ‘reactive reconciliation’. However, the use of generic factors applied across differing time scales and material types often disguises the causes of the error responsible for the discrepancy. The root causes of any given difference can only be identified by analyzing the information behind any difference and, then, making changes to methodologies and processes. This practice is called prognostication, or ‘proactive reconciliation’, an iterative process resulting in constant recalibration of the inputs and the calculations. Prognostication allows personnel to adjust processes so that results align within acceptable tolerance ranges, and not only to correct model estimates. This paper analyses the reconciliation practices performed at a gold mine in Brazil and suggests a new sampling protocol, based on prognostication concepts.

INTRODUCTION

The mining chain is better described as a sequence of unit operations, each involving a specific level of knowledge. The increasing complexity of individual operations, as well as the necessary integration throughout the chain, requires a systemic approach to adequately assess the entire process. This context holds the practices for reconciliation, which is the practice of comparing the tonnage and average grade of ore predicted from resource and grade control models with the tonnage and grade generated by the processing plant. As great discrepancies between these values are a common problem in several gold and base metals mines around the world, there is a need for adopting strategies to minimize such a problem.

Historically, reconciliation has been done in a reactive way, *i.e.*, comparing the grades produced by the processing plant with the grades estimated by the resource models and then applying factors, such as the MCF, to future estimates in an attempt to better predict how the operation may perform. However, after Morley (2003), the use of generic factors is no longer recognized as industry best practice, as the application of a factor will often disguise the causes of the error responsible for the discrepancy. The correct practice of reconciliation should be done in a proactive way, *i.e.*, identifying and analyzing the information behind any variance and, then, making changes to methodologies and processes so that estimates and measurements realign. This method turns estimates into forecasts and forms the basis for decision making to ensure that what happens in the future will match the plan or schedule. Morley named it 'prognostication', an iterative process used to ensure that the variance between original estimates and actual results stay within acceptable ranges.

After Shofield (2001), mine reconciliation is seen, for many, as the ultimate test of the quality of grade and tonnage estimates in resource or grade control models. However, without accurate sampling, capable of providing reliable data, any statistical analysis is nonsense. In general, a sample is intended to represent a particular sampling unit, or volume of material. The sampling methodology is considered correct and unbiased if all of the particles in the sampling unit have exactly the same probability of being selected for inclusion in a random sample, which is called unbiased sampling. Correct sampling equipment, correct operating procedures and well-designed processes are essential to successful sampling, guaranteeing the selection of representative samples. Nevertheless, due to a lack of knowledge of the fundamentals of sampling theory, many companies lose millions every year with reconciliation problems. Studies demonstrate that even little improvements in sampling processes result in significant benefits for an operation.

The samplers, on the other hand, should be designed to guarantee unbiased samples. And the sampling techniques should be based on theories that allow minimizing sampling errors, assuring the selection of representative samples. In this way, the statistics and geostatistics are powerful tools, since they allow the analysis of sampling errors by using variograms and auxiliary functions.

This paper discusses and compares the practices of reconciliation and prognostication performed at a gold mine in Brazil, which is well grounded on adjustments of sampling methodologies and processes. A new sampler and a new sampling protocol have been proposed, with the intention of eliminating significant sampling biases by taking preventive actions.

Sources of Errors

The first, and more obvious, source of errors is sampling. In some cases, blast hole sampling can consistently underestimate or overestimate the real grade of an ore body. Sampling biases are probably the most difficult errors to estimate and certainly deserve special attention. According to Gy (1998), “heterogeneity is seen as the sole source of all sampling errors” and is the only condition in which a set of units can be observed in practice.

Successful reconciliation can be illusory. In many cases, errors at one point of the process are offset by errors at other points in the operation, resulting in an excellent reconciliation (Crawford, 2004). However, this fact can hide compensating biases in the system that may surface someday.

The usefulness of reconciliation data remains dependent on the quality and reliability of the input data, *i.e.*, estimates and measurements. The resource estimates are themselves dependent on the underlying sample data and the processes used to generate the resource estimates (including short-term grade control estimates). All of these measurements have some degree of associated error or confidence level.

The reliability of the sampling results depends on several factors – namely, the characteristics of the mineralization, sampling quality, sample preparation and sample assaying – and can be evaluated by the variability of sample grades (precision) and the accuracy of the results (bias). The variability of sampling results can be broken down into three main sources: (1) the inherent heterogeneity, (2) the sampling errors, including sample preparation, and (3) the assaying errors. It is important to understand and quantify these errors, so that the confidence of the final sample results can be reported and used in reconciliation investigations (Noppé, 2004).

Reconciliation × Prognostication

Reconciliation is a common activity carried out at most mines around the world and can be a useful tool to evaluate sampling accuracy along the grade control processes. Sampling is part of the grade control protocol and must be performed in order to minimize errors and assure the quality of the final estimate. Proper block estimation for short-term mine planning requires good sampling practices, and should improve result in terms of reconciliation.

Reconciliation can be defined as a comparison between an estimate (resource or grade control model) and a measurement (survey information or the official production, usually from the processing plant). Dividing the produced grade by the grade estimated by the resource models results in a factor (MCF) that can be applied to resource or grade control estimates to more accurately define what the processing plant may produce.

However, this is not the best industrial practice of reconciliation, since the main objective of any reconciliation system should not be to generate a list of factors used to correct estimates, but to allow personnel to adjust processes so that results align within acceptable tolerance ranges. This will result in significant benefits for the operation and provide a basis for ongoing improvement.

Prognostication is an alternative to reconciliation, and consists on constantly collecting and analyzing key measurements that are used to calibrate critical estimates in an iterative process. When variations occur, they are analyzed and corrective action is taken to ensure the estimates and measurements realign. These actions include changes to sampling protocols, changes to sampling techniques, use of correctly designed samplers etc., intending to improve data reliability and estimate quality. Prognostication, therefore, allows the correction of methodologies and not simply a correction of model estimates.

It is possible to perform a proper reconciliation practice only if there is information about all of the mining operations, and this information has to be based on reliable data. Therefore, the optimization of sampling techniques has an essential importance for the development of a reliable reconciliation system, since only a correct sampling protocol can provide reliable data.

METHODOLOGY

According to Crawford (2004), reconciliation does not simply examine the resource model against mining results. In practice, each step of the operation must be examined sequentially from model to mine, mine to mill, mill to smelter or refiner or to final sales. This study analyses the second step of reconciliation, also called ‘mine to mill’, which compares two estimates: the first based on grade control samples (mine) and the second based on head samples (mill).

The grade control samples, in many mines, result from blast hole sampling, which has two main advantages: (1) the blast hole spacing is small, providing a relatively high sampling density per ton of material, and (2) since the blast holes must be drilled anyway, there is no additional cost. In most cases, however, sample recovery from blast holes is poor and the recovered material exhibits particulate segregation and is not representative of the total sample (Schofield, 2001). Poor sampling precision is common with blast hole sampling, but sample bias caused by particle size and density segregation is a more serious problem. One of the main causes of this bias is the loss of fines, which can lead to an underestimate or overestimate of the ore grade (Snowden, 1993).

According to Bongarçon and Gy (2002), a sample is said to be correct when any fragment in the lot to be sampled has the same probability of being selected in the sample as any other one. And if a sample is correct and sufficiently reproducible, it’s automatically qualified as representative. Therefore, a sample is said to be representative if the two following conditions are met: (1) it is unbiased, and (2) it has a sufficiently small variance. Unfortunately, it is much easier said than done. In practice, correct sampling methods are not that simple, but as the risk of bias is never acceptable, we must reject any sampler or sampling procedure eventually incorrect, because in this case there’s no assurance of sample representativeness.

The previous sampling method performed at the mine for the short-term plan was sampling the pile disposed around the blast hole, after drilling, using a shovel. Four increments were taken from the pile and constituted an approximately 3kg-sample. This practice breaks the main law of the sampling theory: any particle shall have equal probability to be extracted. Sampling using a shovel is not a probabilistic method, as selected particles are assumed to have the same characteristics of all others unreachable by the shovel. Since we cannot estimate the precision of manual sampling, it is not a reliable method (Grigorieff *et al.*, 2002).

Stationary Sectorial Sampler

The following experimental procedure is intended to minimize the errors previously described, by designing a sampler that could reduce the loss of fines and increase sample representativeness. The solution was the use of a stationary sectorial sampler, proposed by Pitard (1993), and positioned around the blast hole to be drilled. The sectorial cutter is a pie-shaped bucket easily removed from the frame, and for the cutter to be correct it should be radial with the center of the blast hole. The bucket should also be deep enough not to overflow before the end of the drilling. This sampler minimizes the risk of contamination and the errors introduced by manual sampling.

To the sampler proposed by Pitard, a modification was suggested so as to reduce the loss of fines, a constant problem in blast hole sampling. A semi-spherical cupola, made of acrylic material, was added to the sampler, respecting the conditions of extraction correctness. Figure 1 illustrates the proposed sampler.

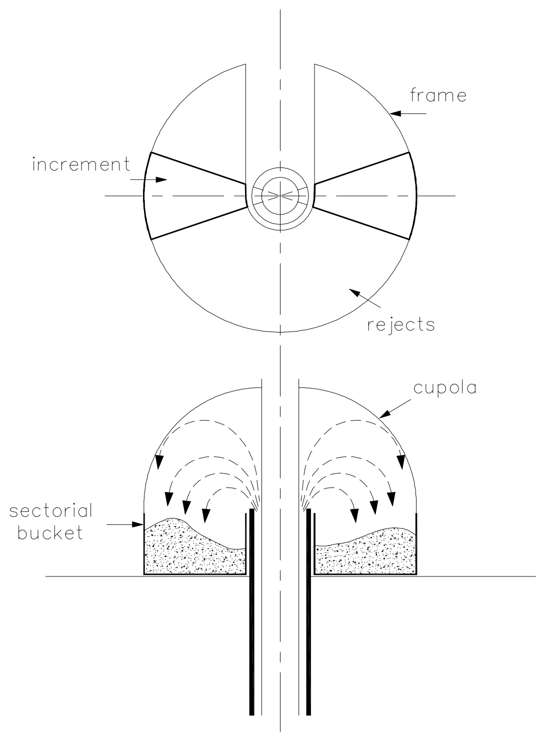

Figure 1 - New stationary sectorial sampler proposed.

The sectorial sampler is assembled to the driller and generates two samples, one per bucket, weighting approximately 3 kg each. The sectorial buckets are positioned in two quadrants of the sampler, each one collecting an increment represented by a sector of the total sample. Figure 2 shows how the sampler is assembled to the driller.

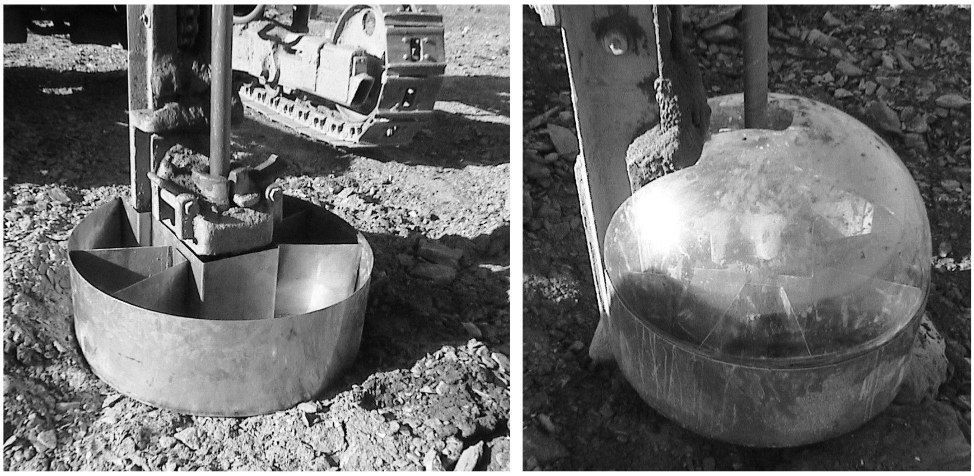

Figure 2 - Stationary sectorial sampler assembled to the driller.

Sampling Methodology

The new sampling methodology proposed was based on Morley's prognostication concepts, where steps are taken sequentially, following an iterative process where changes to sampling protocols aim to reduce estimate errors as well as variances of sampling errors. Each step of this process intends to improve sample quality, consequently increasing its representativeness.

The new reconciliation method consisted of comparing sample grades collected at the plant (head samples) with sample grades collected at the mine (grade control samples). According to Crawford (2004), this is the second step of reconciliation, also called mine-to-mill. This method included five sampling campaigns, referred to five different mining blocks, which, after mining and crushing stages, were sampled on the conveyor belts that fed the processing plant. The head samples consisted of 1m-belt material, weighting approximately 50 kg each sample. The grade control samples consisted of material from blast holes, using the sectorial sampler previously described, which provided two samples of approximately 3 kg each.

A total of 480 samples were sent to the laboratories for preparation and chemical analysis, including head samples and grade control samples. All of them were prepared in the same laboratory and followed the same procedures of drying, splitting and crushing. From each sample three aliquots of approximately 50 g each were taken for gold, arsenic and sulphur analysis.

RESULTS

Table 1 shows the followed steps, the changes to sampling protocol, the main objectives of proactive reconciliation and comments on the impact of various decisions made. For a better understanding of the entire process, the information is presented as a table, where the steps are shown chronologically.

Table 1 - Steps of proactive reconciliation in the mining industry.

step	data source	changes	objectives	results
1	mine	replacement of manual sampling by a sectorial sampler	minimize the delimitation and the extraction errors	smaller variance of the sampling error
2	mine	insertion of a rubber sealing above sampler's cupola	minimize sample biases caused by loss of fines	smaller variance of the sampling error
	plant	sampling at the plant (crushing stage)	calculate grade estimate errors	not a representative value; based on 2h sampling and 5% (mass) of block
3	plant	greater number of increments at crushing stage	increase reliability on grade estimates	representative, but not ideal, value; 70% (mass) of block sampled
4	mine	exclusion of rubber sealing; increase of drilling water	eliminate the bias caused by the rubber and reduce loss of fines	the worst estimate, due to fines washing; greater error variance
	plant	greater number of increments at crushing stage	increase reliability on grade estimates	representative value; 90% (mass) of block sampled
5	mine	re-insertion of the rubber sealing; drilling without water	minimize biases caused by washing the fines	smaller error variances; better estimates of average grades
	plant	smaller time interval between increments collected	increase reliability on grade estimates	the most representative value; 100% (mass) of block sampled

Figure 3 shows, for each block, the average gold grades estimated by the application of the MCF to model estimates and by the different sampling methods at the mine and at the processing plant.

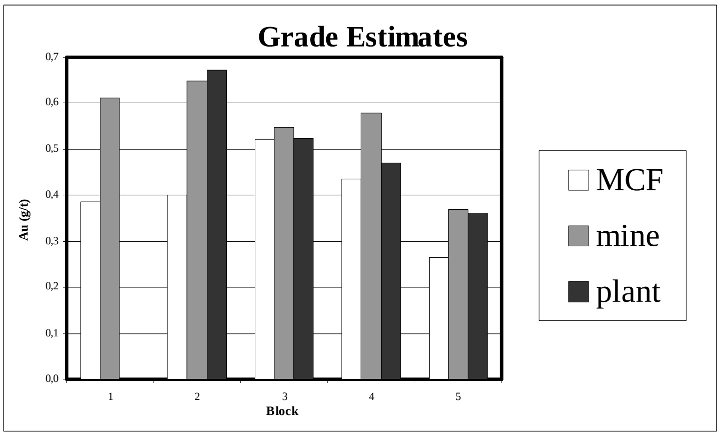

Figure 3 - Gold grade estimated by different sampling methods.

STATISTICAL ANALYSIS

According to Isaaks and Srivastava (1989), information extracted from a dataset or any inference made about the population from which the data originate can only be as good as the original data. Therefore, before submitting any data for statistical or geostatistical analysis, it's especially important to verify its quality and authenticity. If inconsistencies exist, they should be checked and resolved before statistical analysis proceeds. The authors suggest four steps to catch gross errors and help data cleaning: (1) sort the data and examine the extreme values. If they appear excessive, investigate their origin and try to establish their authenticity. Original sample diaries or sampling logs are useful sources of information. (2) Locate the extreme values on a map. Note their location with respect to anomalous areas. Are they located along trends of similar data values or are they isolated? Be suspicious of isolated extremes. (3) Check coordinate errors by sorting and examining coordinate extremes. (4) Examine a posting of the data. Do the samples plot where they should?

Following the authors' suggestions, sampling results were analyzed individually. After checking sample diaries, where information about eventual problems could be found, outliers and unreliable data were excluded from statistical analysis. Table 2 shows the results for each block and each sampling method. The lines related to the MCF represent the average gold grade provided by the application of the MCF to resource model estimates. This is still common practice at many mines around the world.

Table 2 - Comparison between reactive and proactive reconciliation practices.

block	data source	number of samples	average grade Au (g/t)	error mean m(SE)	error variance s^2(SE)	grade estimate error PROACTIVE	grade estimate error REACTIVE
1	MCF		0,385	*	*	*	*
	mine	12	0,612				
2	MCF		0,400	-0,024	0,054	3,5%	40,6%
	mine	20	0,649				
	plant	6	0,673				
3	MCF		0,522	0,029	0,053	4,6%	0,38%
	mine	20	0,548				
	plant	18	0,524				
4	MCF		0,436	0,103	0,040	22,7%	7,4%
	mine	59	0,578				
	plant	49	0,471				
5	MCF		0,265	-0,011	0,028	1,7%	26,9%
	mine	72	0,369				
	plant	22	0,363				

* No sampling performed at crushing stage and, therefore, no reference value to calculate errors.

The analysis shows that reactive reconciliation practices can't predict and/or control estimate errors and, therefore, they are unable to properly assist mine planning. The proactive reconciliation, on the other hand, helped us to understand these errors, and this comprehension allowed changing sampling methodologies in order to minimize these errors. This fact alone is an advantage of prognostication. The chronological sequence has shown also a continued decrease of sampling variances and grade estimate errors, which indicates an increase of sample representativeness.

The exception, not less important than the rule, was made to block 4, that besides exhaustive sampling, presented variances and errors above the expected values. The probable cause of these variances was the increase, particularly for this block, of the quantity of drilling water, in an attempt to diminish the generation and consequent loss of fines. What really happened was that washing the fines back to the blast hole increased the sampling extraction error. And, therefore, the first condition of sample representativeness wasn't satisfied, *i.e.*, the condition of an unbiased sample. Fortunately, the statistics confirm that without reliable data any analysis is nonsense.

DISCUSSIONS

It is known that the first, and more obvious, source of errors is sampling, and that sampling bias is probably the most difficult error to be measured. After Grigorieff (2002), the variance of the overall estimation error is 80% due to sampling, 15% to preparation and 5% to chemical analysis.

A sampling system should be dimensioned so as to minimize the errors we cannot eliminate and to eliminate the rest, in a way to obtain the precision and accuracy required. The method of prognostication presented in this work tried to minimize and/or eliminate these errors, by suggesting changes to sampling methodologies and equipments. A prognostication method should always try to improve sample representativeness and maximize its precision and accuracy. The results of prognostication practices showed, chronologically, improvements in sample representativeness, translated by:

- Accuracy: smaller error between grades estimated by the sampling method (mine) and the reference grade (plant).
- Precision: smaller variance of sampling errors both at mine and plant.

CONCLUSIONS

Even knowing the concepts of sampling theory, we are not always able to do, in industrial practice, what is theoretically correct. Gold has its peculiarities itself, especially regarding the segregation effect. The density of gold is enormous, promoting strong segregation phenomena as soon as gold is liberated. Furthermore, the gold content of an analytical subsample and the gold content of the sample from which it was selected can be very different. All these problems are amplified as the gold grade becomes lower, as gold deposits become marginal, and as the distribution of gold in rocks becomes erratic. This study worked with a very low-grade gold deposit, using blast hole samples, which in general present poor sampling precision and biased samples, due to size and density segregation.

Starting from the worst situation, our study tried to develop a sampling methodology that, at least, allowed us to know the errors involved, so that the final results could be used consciously in reconciliation calculations. Special attention was given to the generation of reliable data, or representative samples, following the basic principles of selection of correct samples.

As an alternative to reactive reconciliation, we introduced proactive reconciliation, or prognostication, which is defined as the act of forecasting or predicting something in the future from present indications or signs, as a method for improving the process. The results show that:

- As the error variance $s^2(SE)$ decreases, the sampling precision increases.
- As the error mean $m(SE)$ decreases, the sampling accuracy increases.
- With better precision and accuracy, sample representativeness increases and, consequently, the input data reliability.

As shown, proactive reconciliation can bring significant benefits to the mining industry. It is evident that sampling errors are far from being completely eliminated, but a first step was taken, and improvements were demonstrated. When we minimize errors that cannot be eliminated and apply correct sampling protocols to eliminate the other errors, we are able to create a model which estimates become forecasts, or prognostics, assuring that what happens in the future will match the present plan.

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