Available online at www.sciencedirect.com

SCIENCE DIRECT®

Chemometrics and Intelligent Laboratory Systems 74 (2004) 209–213

Chemometrics and intelligent laboratory systems

www.elsevier.com/locate/chemolab

The economic impact of correct sampling and analysis practices in the copper mining industry

Pedro Carrasco*, Pablo Carrasco, Eduardo Jara

Codelco, Huerfanos 1270, Santiago, Chile

Received 1 September 2003; received in revised form 1 March 2004; accepted 1 April 2004
Available online 26 June 2004

Abstract

Incorrect sampling operations can cause huge economic losses to the mining industry. The main objective of this paper is to illustrate with four real case studies the tremendous economic impact that incorrect sampling and assaying can cause. On the other hand, when the Sampling Theory is applied correctly in the mining industry, a considerable amount of money can be saved.

Keywords: Sampling; Sampling Theory; Economic impact; Hidden losses; Bias

1. Introduction

After 50 years of the magnificent scientific and practical contribution of Dr. Pierre Gy's Theory of Sampling [1–5], the copper mining industry is still not fully aware of its paramount importance. This is a surprising fact because along the value chain of the mining business, from rock to cathodes, many critical decisions are based on samples and assays. An incorrect sampling and assaying process can lead to bad decisions that can cost billions of dollars during the life of a large mining company. Some of the reasons for this inconsistency are:

- Incorrect sampling generates *hidden* losses that do not appear in the accountant's books, therefore, top management does not become aware of them.
- People focus on effects and not on causes of problems (e.g.: Incorrect sampling practices). This attitude creates unhappiness, time losses, money losses, unfairness, and does not solve anything.
- If the people involved do not deeply understand the sources of the variability of the mining processes, the losses are difficult to discover and their economic impact is difficult to estimate.
- Generally, the mining industry has low synergy. Most professionals are focused on solving their own problems, which are not necessarily aligned with the objectives of the company that is to produce high quality cathodes at the lowest possible cost. As a consequence, they do not collaborate with each other, they do not know each other and therefore develop communication problems.
- An isolated sampling community which has been unable to communicate the relevance of sampling to top management in economic terms.
- Formal University courses and research programs in Theory of Sampling are rare, hence, geologists, mining engineers, metallurgists and chemists commonly have a poor background on the subject of sampling.
- The initiation in Sampling Theory is difficult because the fundamental books are cryptic, hence not easy for beginners to read.

Therefore, the main purpose of this paper is to illustrate the economic impact of incorrect sampling and assaying practices by describing four case histories collected throughout 42 years of experience in the mining industry world wide.

1.1. Case study 1. Sampling density and its relevance in the assessment of the economic value of high-tonnage–low-grade heap leaching copper project

When estimating the economic value of mining ventures, the selected sampling pattern is of capital relevance to understand the variability of the ore grade. This case study examines this issue.

* Corresponding author.
E-mail address: pcarrasc@codelco.cl (P. Carrasco).

0169-7439/$ - see front matter
doi:10.1016/j.chemolab.2004.04.013

The copper spatial distribution of a low-grade oxide zone of a porphyry copper deposit in Northern Chile has been modeled by conditional simulation methods [6–8]. The simulation grid was 5 × 5 × 15 m. Then several drilling patterns were chosen and the copper grade was estimated by kriging [9–11].

The results of one realization of the conditional simulation and the estimation can be seen in Fig. 1.

As can be seen from this figure, the perception of natural variability is a direct consequence of the information density.

In order to calculate the economic impact of the several open pit scenarios, mining plans were developed. The net present value was estimated by [12]:

$$B_i = [V_i(m) - p(t)] \cdot t_i^{1-e^{iN}} - I(t) \tag{1}$$

where: B_i = net present value (MUS$); $V(m)$ = value of 1 ton of ore (US$); $p(t)$ = cost of production of 1 ton of ore (US$) = 5 US$/ton; t = annual rate of production (ton/year) = 30 Mt/year; i = discount rate = 10%; N = life of mine (years) = 30 years; $I(t)$ = investments (MUS$) = 640 MUS$; m = mean grade above cutoff grade (%Cu); $V(m) = 22.04 * \mathrm{pr} * R * m$; where: pr = copper price = 0.8 US$/lb; R = metallurgical recovery in % = $(m - 0.1008) * 0.9/m$.

Table 1 shows the results.

This example clearly shows that:

- The sampling density has an important impact in the perception of the value of the mining business.

Table 1
Net present values as a function of the drilling pattern and estimated by mining engineers BEFORE the investment decision

Drill pattern (m*m)	Mean grade (%Cu)	Variance (%Cu)**2	Tonnage (Mt)	NPV (MUS$)
150 by 150	0.551	0.014	801	− 49
100 by 100	0.650	0.042	672	345
50 by 50	0.667	0.064	613	389
20 by 10	0.675	0.674	602	421
10 by 5	0.685	0.690	585	450

- An improper drilling pattern results in misleading economic decisions, for example, to dismiss a good business opportunity, to design a mill with incorrect capacity, and to overestimate a waste dump capacity.
- The variability and mean grade of the copper content estimation are a function of the drilling pattern and hence the economic value. An improper sampling density combined with the smoothing effect of kriging results in an underestimation of both the variability and mean grade of the copper content, and therefore the economic value. As a consequence, a selective mining plan is not possible hence the underestimation of the economic value.
- When mining, proper sampling and good grade control practices result in an increase in NPV estimated in feasibility studies.
- A multidisciplinary team of experts in all the aspects of the mining business is fundamental in evaluating mining ventures when the information is limited. In this context, the expert on Sampling Theory and Practice plays a

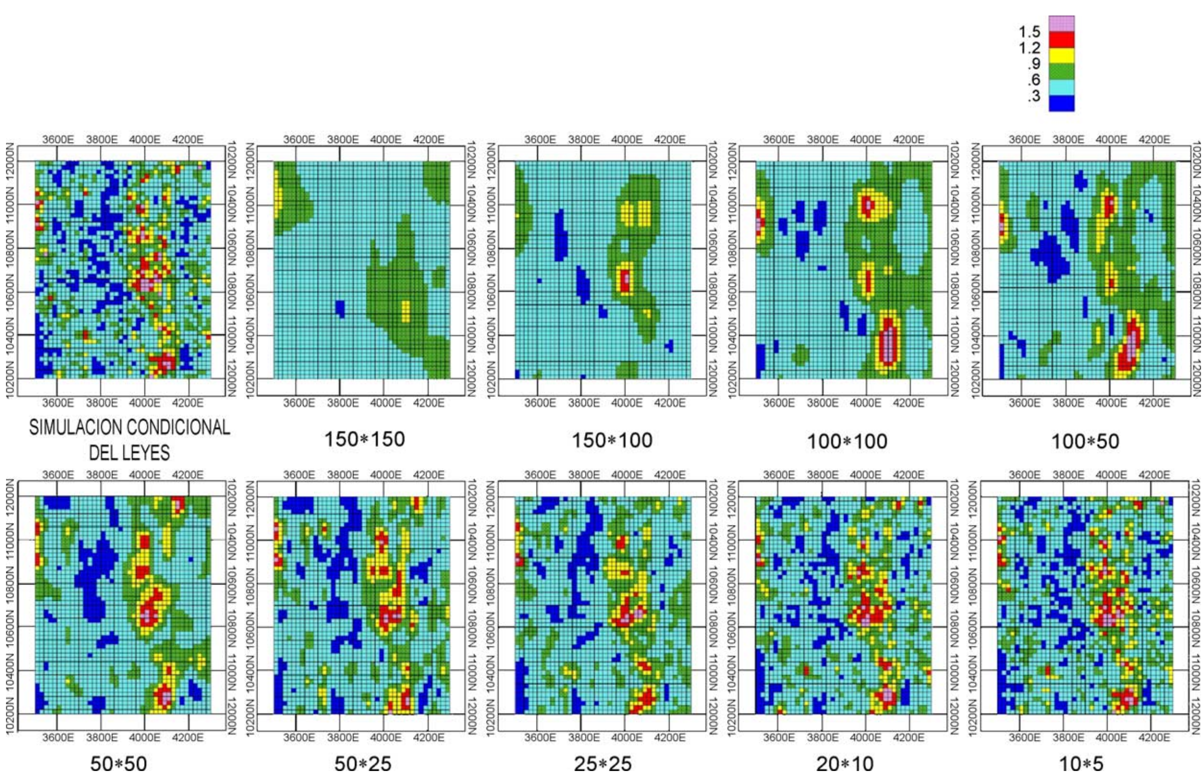

Fig. 1. Information effect on grade estimation.

fundamental role, because many important decisions of the value chain are based on samples. If the sampling is incorrect, the evaluation process collapses.

1.2. Case study 2. What happened when a proper sampling device was installed in a tail discharge?

A half million dollar sampling station was installed in order to measure the tail grade and the pulp density in a large copper operation in central Chile. The station was built because the tails were about to be sold to another company which treated them downstream and therefore the grade and the tonnage had to be estimated properly. The sampling station was designed in order to follow all the rules of equiprobable sampling as stated by the Sampling Theory [3]. The flow rate was 96.000 tons/day and the tail grade was assumed to be 0.15% copper by traditional metallurgical balance.

The station proved the traditional estimation of the tail grade wrong, which was actually 0.2% copper and probably in the past the bias was greater because of worse metallurgical techniques and higher-grade secondary ore. This operation has been running for 87 years.

Let us calculate the losses in a time frame of 20 years:

The annual losses are:

$$\mathrm{FA} = 96.000\frac{\text{ton}}{\text{year}}*0.05\%*365\ \text{days}100\%$$

$$= 17,520,\ \text{tons of copper per year.} \tag{2}$$

Considering an average copper price of 1 dollar per pound, the annual loss is: 175,207*2200*1 ≈ 38.544MUS$.

If we consider an average interest rate of 10% the total lost is [14]:

$$\mathrm{NPV} = \left[\frac{(1+i)^n - 1}{i}\right]A \tag{3}$$

$$\mathrm{NPV} = \left[\left(\frac{(1+0.1)^{20} - 1}{0.1}\right)*38.544\mathrm{MU\$}\right] \approx 2207\mathrm{MU\$!} \tag{4}$$

where: NPV = net present value; A = yearly loss; i = interest rate; n = number of years.

We can conclude from this case study:

- Correct sampling practices and equipment discovered hidden losses of an incredible economic magnitude, more than 2 billion dollars in this particular case.
- When top management is not aware of the losses, the continuous improvement is difficult because they think the operation is working properly and actually it is not. For example, an underestimation of the tail implies a severe overestimation of the recovery. This incorrect vision condemns investment on better metallurgical processes.
- Correct sampling practices are not expensive compared with the losses they can avoid.
- Correct sampling practices are a matter of awareness.
- Metallurgical balance based on incorrect sampling can be very misleading. It leads to incorrect operational decisions and conceals the causes of problems, particularly when people use software to blindly correct the differences.
- Incorrect sampling practices lead to economic inefficiency and to an unsustainable exploitation of mineral resources.

1.3. Case study 3. Economic losses produced by an inefficient grade control system caused by incorrect sampling of blast holes

This happened in a porphyry copper operation located in Northern Chile. Blast holes samples were taken in a very primitive way by hand without any respect of the equiprobable selection rules established by the Sampling Theory. A 2-ton lot was represented by a 250-g sample with a 2-cm top fragment size. This sampling procedure generated a huge fundamental error combined with operator-dependent delimitation and extraction non-constant biases.

The variographic analysis of the blast holes copper grade shows a large nugget effect (70% of the total variance) and a much higher variability than the diamond drill copper grade which had a much smaller support. Therefore, the conclusion is that incorrect sampling introduces an artificial or irrelevant variability component which does not belong to nature. The reasons for this kind of sampling were speed, low operational cost and the illusion of a high degree of geological homogeneity.

In order to estimate the magnitude of the losses, the following procedure was used. [13]:

- Lognormal behavior of both "real" estimated copper grade (Z) and kriging estimated grade ($Z°$) of selected mining units was assumed and verified, respectively.
- The mean grade variance and covariance of both random variables Z and $Z°$ were known as well. The lognormal joint probability density function (Jpdf) could be calculated [15]. Fig. 2 shows a scatter plot between the "real" estimated copper grade (Z, Y-axis) and the estimated kriging grade ($Z°$, X-axis).
- From the Jpdf, it is possible to compute the proportion of tonnage of ore sent to the waste dump, of waste sent to the mill and the mean grades above cutoff. In this particular case, the total ore reserve is 500 Mt, the yearly mining rate is 50 Mt, the cutoff grade is 0.4% copper, the life of mine is 10 years, and the stripping ratio is 1:1. The tonnage of waste sent to the mill is 10.715 millions tons per year at 0.35% copper, and the tonnage of ore sent to the waste dump is 9.225 millions tons per year at 0.49% copper. The metallurgical recovery is 80%, the

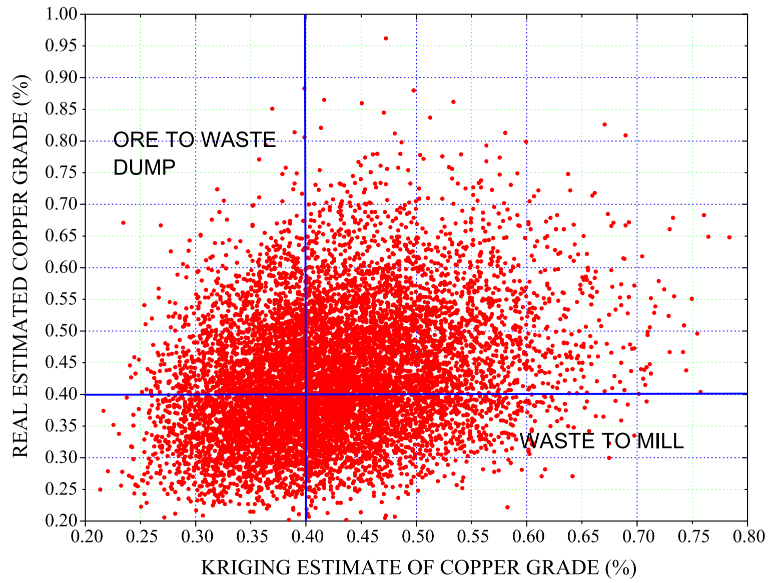

Fig. 2. Joint probability density function of the estimated real copper grade and the kriging estimated copper grade.

price is US $1 per pound of copper and the cost is US $7.05 per ton.

- The present value of the misclassification is:

$$PV = B^{+} - B^{-} \tag{5}$$

where B^{+} is the net present value of sending ore to the waste dump and B^{-} is the net present value of sending waste to the mill:

$$B^{+} = (22*0.8*1*0.4879 - 7.05)*9.225*\left(\frac{1 - e^{-10*0.1}}{0.1}\right) \approx 89.63\text{MUS\$} \tag{6}$$

$$B^{-} = (22*0.8*1*0.34525 - 7.05)*10.715 *\left(\frac{1 - e^{-10*0.1}}{0.1}\right) \approx -65.95\text{MUS\$} \tag{7}$$

Then the total loss is:

$$B^{+} - B^{-} \approx 156\text{MUS\$} \tag{8}$$

By applying an analogous heuristic, it can be proven that correct sampling practices result in a much lowest misclassification, actually 2.4 Mt/year of ore to the waste dump at 0.427% copper and 4.4 Mt of waste to the mill at 0.373% copper. The total loss is:

$$B^{+} - B^{-} \approx 22\text{MUS\$} \tag{9}$$

It can be concluded from this example that:

- Incorrect sampling practices generate considerable value losses. On the other hand, correct sampling could save significant amounts of money.
- Even with correct sampling practices, it is difficult to totally avoid the losses. They can only be minimized.
- An efficient way to discover the hidden losses of misclassification is by applying statistical/geostatistical thinking, to understand the sources of the different components of variability and to understand in a very clear way that estimation is never equal to reality [16].
- In this case study, the mine grade has to be greater than the mill grade due to the fact that waste is sent to the mill and ore is sent to the waste dump. Therefore, it is naive to expect equal mine and mill grades in reconciliation exercises. Also, constant mine correction factors are an illusion.
- Incorrect sampling practices lead to poor estimates; therefore, economical inefficiency and unsustainable recovery of natural resources are the consequences.

1.4. Case study 4. Losses caused by analytical inaccuracy

In 1970, a chemical laboratory of a large copper mining operation in Northern Chile [17] had a bad response time because the large amounts of samples are to be assayed. The analytical method was atomic absorption. In order to improve the performance, the chief chemist decided to change to XRF. The change reduces the cost and the response time. Only one geological matrix (high-grade secondary sulfides) was considered for calibration. Neither blind duplicates, nor standard reference materials were used at the time in order to monitor the precision and accuracy of the assaying process. Meanwhile the exploration geologists were sending samples from a neighbor deposit to the laboratory for copper assays. The matrix was very different (copper oxides). Because this fact was not reported to the chemist, the resulting assays were biased by 0.06% copper. Considering a yearly mining rate of 32 Mt, a recovery of 80%, an operational lifetime of 20 years, a price of US$1 per pound of copper, and a discount rate of 10%, the economic bias caused by the analytical bias is estimated as follows:

From Eq. (1):

$$B_1 = [V_1(m) - p(t)] \cdot t \frac{1 - e^{iN}}{i} - I(t) \tag{10}$$

$$B_2 = [V_2(m) - p(t)] \cdot t \frac{1 - e^{-iN}}{i} - I(t) \tag{11}$$

$$\Delta B_i = [\Delta V_i(m)] \cdot t \frac{1 - e^{-iN}}{i} \tag{12}$$

$$\Delta V(m) = 22 \cdot Pr \cdot R \cdot \Delta m$$

$\Delta V(m) = 22{*}1{*}0.8{*}0.06 = 1.056$, then the economic bias in net present value terms is:

$$\Delta B_i = 1.056{*}32{*}\frac{1 - e^{-0.1{*}20}}{0.1} \approx 292\text{MUS\$}$$

The lessons from this study are:

- The economic consequences of analytical biases can be of considerable magnitude. In a low-grade deposit, this magnitude can be similar to the estimated profits.
- Analytical accuracy is essential for the correct economic assessment of a mining project. Actually, the final objective is to get a good assay not just a good sample.
- Communication between the protagonists of the mining business is relevant as well as alignment with the business objectives.
- The systematic and continuous use of blind duplicates, standard reference materials and blanks is very important in order to assure the quality of the analytical process.

2. Concluding remarks

Improper sampling and assaying practices can produce monumental value losses to the mining industry world wide. For a single big company, the amount of money lost in a time frame of 20 years could be greater than two billion dollars. Therefore, incorrect sampling and assaying procedures lead to economic inefficiency and unsustainable exploitation of natural resources jeopardizing the wealth of future generations and adding unnecessary negative externalities to society. The mining industry has a magnificent opportunity to increase their economic performance by discovering hidden losses. This can be done by applying the principles of the Sampling Theory, statistical and geostatistical thinking, effective cronostistical process control and by encouraging the work of multidisciplinary high level experts aligned with the main objectives of the mining business.

Acknowledgements

The authors wish to thank Mr. Juan Villarzu, CEO, Mr. Juan Enrique Morales, corporate Resources and Development Vice President and Mr. Edmundo Tulcanaza, corporate Manager of Mineral Resources Evaluation, CODELCO Chile, for their strong support in the implementation of good sampling and assaying practices in the company. We are also grateful to Francis Pitard for his wise advise and lectures on sampling and assaying practices over the last 10 years. We are indebted to Dr. Pierre Gy for a wonderful gift: The Sampling Theory.

References

[1] P. Gy, in: L'Echantillonage des minerais en Vrac, vol. 1, Revue de l Industrie Minérale, St-Etienne, France, 1967, 15 Janvier, Numéro Spécial.

[2] P. Gy, in: L'Echantillonage des minerais en Vrac, vol. 2, Revue de l Industrie Minérale, St-Etienne, France, 1971, 15 September, Numéro Spécial.

[3] P. Gy, Sampling of Particulate Materials Theory and Practice. First edition (1979), Second revised edition (1982), Elsevier, Amsterdam xvii, 431 pp.

[4] P. Gy, Sampling for Analytical Purposes. Wiley, Chichester. April 1998 150 pp. Second edition (June 1999).

[5] F. Pitard, Pierre Gy's sampling theory and sampling practice, second edition, CRS Press, USA, 1993, 488 pp.

[6] A.G. Jornel, C.J. Huijbregts, Mining Geostatistics, Academic Press, London, 1978, 599 pp.

[7] C. Lantuéjoul, Geostatistical Simulation, Models and Algorithms, Springer, Paris, 2002, 256 pp.

[8] P. Carrasco, E. Jara, El valor de la información en las decisiones mineras, Minería Chilena 84 (1994) 29–39.

[9] G. Matheron, Les Variables régionalisées et leur estimation. PhD thesis, Masson, Paris, 1965, 212 pp.

[10] M. David, Geostatistical Ore Reserve Estimation, Elsevier, Amsterdam, 1977, 364 pp.

[11] J.P. Chiles, P. Delfiner, Geostatistics. Modeling Spacial Uncertainty, Wiley, USA, 1999, 695 pp.

[12] G. Matheron, P. Formery, Recherche d'optima dans la reconnaissance et la mise en exploitation des gisements minieres, Annales des Mines 220–237 (VI) (1963) 260–277.

[13] P. Carrasco, Caracterización de la Heterogeneidad de Constitución en Menas de Pórfidos Cupríferos, Memoria de Título (Unpublished), Universidad Católica del Norte, Chile, Departamento de Geología, 2003, 89 pp.

[14] B. Leland, et al., Engineering Economy, first edition, McGraw-Hill, USA, 1998.

[15] G. Matheron, Traité de géostatistique appliquée. Tome 1 (1962) 334 pp, Tome 2 (1963) 172 pp. Editions Technip, Paris.

[16] G. Matheron, Estimer et choisir. Cahiers du Centre de Morphologie Mathématique de Fontainebleu, Fasc. 7, Ecole des Mines de Paris, 1978.

[17] G. Behn, J. Beniscelli, P. Carrasco, P. Cuadra, G. Ferguson, Estimation of resources and engineering of reserves, Radomiro Tomic project, Codelco-Chile, Transactions of the Institution of Mining and Metallurgy 107 (1998) A63–A108 (England).