1 Introduction

Abstract

The estimation of mineral resources is an important task for geoscientists and mining engineers. The approaches to this challenge have evolved over the last 40 years. This book presents an overview of established current practice. The book is intended for advanced undergraduate students or professionals just starting out in resource estimation.

1.1 Objectives and Approach

Our objective is to explain important issues, describe commonly used geological and statistical tools for resource modeling, present case studies that illustrate important concepts, and summarize good resource estimation practice. Wherever possible a common thread will be maintained through the sections including details of theory and references to appendices and other authors, relevant examples, software tools available, required documentation trail for better practice, extensions to handling multiple variables, modeling of other less common variables such as metallurgical properties, and limitations and weaknesses of the assumptions and models used.

There are a wide variety of minerals of interest including industrial minerals such as gravel and potash, base metals such as copper and nickel, and precious metals such as gold and platinum. There are other spatially distributed geological variables such as coal, diamonds, and variables used to characterize petroleum reservoirs. Often, the constituent of interest has variable concentration within the subsurface. A *resource* is the tonnage and grade of the subsurface material of interest. The resource is in-situ and may not be economic to extract. A *reserve* is that fraction of a resource that is demonstrated to be technically and economically recoverable. Estimation of resources and reserves requires the construction of long-term models (life of asset) for the entire deposit, which are updated every 1–3 years of operation. Medium-term models may be built for planning one to 6 months into the future. Short-term models are built for weekly or day-to-day decisions related to grade control or detailed planning.

Constructing numerical models for long, medium or short-term resource assessment includes four major areas of work:

1. Data collection and management;
2. Geologic interpretation and modeling;
3. Grades assignment; and,
4. Assessing and managing geologic and grade uncertainty.

Data collection and management involves a large number of steps and issues. There are books on drilling and sampling theory, such as Peters (1978) and Gy (1982). The richness and complexity of these subjects cannot be covered in detail; nevertheless, it is important that the resource estimator consider subjects that affect the quality of the ultimate estimates. Some background information is provided.

Geologic interpretation and modeling requires that site specific geologic concepts and models are integrated with actual data to construct a three dimensional model of geological domains. This geologic model is a representation of those variables that control the mineralization the most and forms the basis for all subsequent estimation. Often, the geological model is the most important factor in the estimation of mineralized tonnage.

The concentrations of different elements or minerals (grades) are assigned within geological domains. The grades within the different domains may be reasonably homogeneous; however, there is always some variability within the domains. The grades are predicted at a scale relevant for the anticipated mining method. The recoverable resources are calculated considering a set of economic and technical criteria. There are a wide variety of methods available and many implementation aspects must be considered. The chosen method will

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depend on the study objectives, the available data and the professional time available to complete the study.

Resource estimates should be complemented with a measure of uncertainty. All numerical models have multiple significant sources of uncertainty including the data, the geologic interpretation, and the grade modeling. A statement quantifying the uncertainty in the predicted variables is required for good and best practices.

These four main subjects are covered in 14 chapters. Each chapter concludes with an exercise that summarizes the key points and helps interested readers test their understanding of the material presented. No solutions to the exercises are provided.

1.2 Scope of Resource Modeling

The collection, gathering, and initial analysis of data are the first steps in mineral resource modeling. Sufficient quality controls and safeguards are required to achieve an adequate degree of confidence in the data. The overall process of Quality Assurance and Quality Control (QA/QC) should encompass field practices, sampling, assaying, and data management. This is necessary to ensure confidence in the resource model.

The data are subset within different geological domains. These domains may be based on a variety of geological controls such as structure, mineralogy, alteration and lithology. Categorical variable models are constructed to subdivide the data and focus analysis in different regions of the subsurface. Domains are commonly assigned to a gridded block model. The block model must have sufficient resolution to represent the geological variations and provide the required resolution for engineering design. Of course, the number of blocks must not be too large. At the time of writing this book, it is common to use 1 to 30 million blocks. Larger models are possible, but they require more computer resources and managing multiple realizations of many variables becomes time consuming.

Statistical analyses of the available data are required before decisions can be made about geological domains. Mineralization controls interact to control the spatial distribution of grades. Compositing the original data values is common practice. This is done partly to homogenize the support of the data used in estimation, but also to reduce the variability of the dataset. Further statistical analyses are performed to understand and visualize the data distributions and to define the most appropriate form of estimation.

After defining the block model geometry and geological domains, it is necessary to assign grades. The choice of an estimation method and the formulation of plans for grade interpolation are described in later chapters. Special considerations required for simulation are also discussed.

Each step in mineral resource estimation requires assumptions and decisions that should be explicitly stated. Perceived limitations and risk areas should be documented. The process of model validation and reconciliation is iterative. The calibration of a recoverable resource model against production, if available, is particularly important to ensure future predictions are as accurate as possible. Proper and detailed documentation is required for each step. An audit trail must be created during the entire resource estimation process to allow a third party to review the modeling work. Transparency and the ability to allow for peer-reviews are essential components of the work.

1.3 Critical Aspects

The estimation of resources and reserves requires detailed consideration of a number of critical issues. Like a chain, they are linked such that the quality of the overall resource estimate will be equal to the quality of the weakest link; any one of them failing will result in an unacceptable resource estimate. Resource estimators must deal with these issues on a daily basis.

The quality of the mineral resource estimate depends firstly on the available data and the geological complexity of the deposit; however, the resource estimate is also strongly dependent on the overall technical skills and experience of the mine staff, how the problems encountered are solved, the level of attention to detail at every stage, the open disclosure of basic assumptions along with their justifications, and the quality of the documentation for each step.

The emphasis on documenting every aspect of the work is stressed throughout this book because it is the final and, possibly, the most important link in the chain. Justification and documentation of every important decision serves as quality control of the work, because it forces detailed internal reviews. In addition, it also facilitates third-party reviews and audits, which are a common requirement in industry. Some basic issues to be dealt with in resource estimation are briefly discussed next.

1.3.1 Data Assembly and Data Quality

The quality of the resource estimate is directly dependent on the quality of the data gathering and handling procedures. Many different technical issues affect the overall quality of the data. Some important ones are mentioned here.

The concept of data quality is used in a pragmatic way. The concept is that data (samples) from a certain volume will be collected and used to predict tonnages and grades of the elements of interest. Decisions are made based on geological knowledge and statistical analyses applied in conjunction with other technical information. Therefore, the numerical basis for the analyses has to be of good quality to provide for sound decision-making. This is particularly important because a very small fraction of the mineral deposit is sampled.

A second key concept is that the samples should be representative of the volume (or material) being sampled, both in a spatial sense and at the location where the sample is being taken from. *Representative* means that the sampling and analyzing process used to obtain a sample results in a value that is statistically similar to any other that we could have taken from the same volume. Therefore, the sample values are considered to be a fair representation of the true value of the sampled volume of rock. Representation in a spatial sense implies that the samples have been taken in an approximately regular or quasi-regular sampling grid, such that each sample represents a similar volume or area within the orebody of interest. This is often not the case and some correction will be required. If the samples are not representative, then an error will be introduced that will bias the final resource estimate.

In the context of data quality, the technical issues related to sample collection can be divided into those related to field work, and those related to processing of the information. Some of the most important issues in the field include (1) the location of drill holes, trenches, and pits; (2) the type of drill holes used such as open-hole percussion, reverse circulation, or diamond drill holes; (3) the drilling equipment used; (4) the sampling conditions such as the presence of highly fractured rock or groundwater; and (5) sample collection procedures. Core recovery or the sample weight should be recorded. Geologic logging of the geologic characteristics of the samples should be performed. Sample preparation and assaying procedures are critical. The related quality assurance and quality control program is a fundamental element in the process.

Deposit- and mineral-specific sample preparation and assaying protocols must be derived and adhered to throughout the sampling campaign. Heterogeneity tests (Pitard 1993; François-Bongarçon and Gy 2001) are necessary to understand sampling variances and minimize errors.

The construction and maintenance of the sampling database requires a continuous quality control program, including periodic manual and automatic checks. These checks should be performed over all the variables in the database, including grades, geologic codes, collar location and surveys, and density data. Relational databases offer the possibility of easier data handling and improved quality control. But they do not provide quality control by themselves, nor do they replace the need for periodic manual audits.

1.3.2 Geologic Model and Definition of Estimation Domains

Much geologic information is gathered during the investigations performed at different stages of a mining project. The information is used to understand the genesis of the mineral deposit, the distribution of mineralized rock, and to develop exploration criteria for increasing resources.

The level of detail in the geologic description of a deposit steadily increases as the project advances through its different stages. Economic factors are the most important ones affecting the decision of whether or not to proceed with further geologic investigations; therefore, most geologic work is orientated towards finding more mineral resources, and to some extent to more detailed general exploration.

Not all geologic information is relevant to resource estimation. Geologic investigations for resource development should concentrate on defining mineralization controls. Certain geologic details and descriptions are more useful for exploration in that they do not describe a specific mineralization control, but rather provide guidelines for mineral occurrences.

The process of defining estimation domains amounts to modeling the geological variables that represent mineralization controls. The estimation domains are sometimes based on combinations of two or more geologic variables, for which a relationship with grade can be demonstrated. For example, in the case of an epithermal gold deposit, an estimation domain can be defined as a combination of structural, oxidation, and alteration controls. In the case of a diamondiferous kimberlitic pipe, in addition to the geometry of the pipe (lithology), internal waste relics are common, such as granitic xenoliths. The frequency and volume of these within the pipe may condition the definition of estimation domains.

The determination of the estimation domains to use is based on geologic knowledge and should be supported by extensive statistical analysis (exploratory data analysis, or EDA), including variography. The procedure can take a significant amount of time, particularly when all possible combinations of the available geologic variables are studied, but it is typically worth the effort. Estimates are improved when carefully constrained by geological variables.

The definition of estimation domains is referred to as the definition of stationary zones within the deposit. An important part of stationarity is a decision of how to pool information within a specific zone within the deposit, within certain boundaries, or the deposit as a whole. Decisions are based on oxidation zones, lithologies, alterations, or structural boundaries. The stationary domains cannot be too small; otherwise, there are too few data for reliable statistical description and inference. The stationary domains cannot be too big; otherwise, the data could likely be subset into more geologically homogeneous subdivisions.

Defining the estimation domains in resource evaluation is often equivalent to defining the mineralized tonnage available in the deposit. Some units will be mostly mineralized (with the potential of becoming ore), while others will be mostly un-mineralized (almost certainly non-recoverable low-grade resources or waste). The mixing of different types of mineralization should be kept to a minimum to avoid smearing grades across geologic boundaries.

Adequate definition of the estimation domains is an important task for resource evaluation. Mixing of populations within the deposit will generally produce a sub-standard resource estimate that underestimates or overestimates grades and tonnages. It is very rare that any geostatistical technique will compensate for a poor definition of stationarity. A good definition of estimation domains means that only relevant samples are used to estimate each location.

1.3.3 Quantifying Spatial Variability

The grade values observed within a mineral deposit are not independent from each other. Spatial dependency is a consequence of the genesis of the deposit, that is, all of the geological processes that contributed to its formation. The reader is referred to Isaaks and Srivastava (1989) for an accessible discussion on the subject, as well as David (1977), Journel and Huijbregts (1978), and Goovaerts (1997) for more details.

A clear description of the spatial variability (or continuity) of the variables being modeled is desirable. Knowledge of the spatial correlation between different points in the deposit will lead to a better estimation of the mineral grade at an unknown location. The spatial variability is modeled using the variogram and related measures of spatial variability/correlation.

A spatial variability model improves the estimation of each point or block in the deposit. Parameters of the model are important. Attention should be paid to the definition of the nugget effect (the amount of randomness); the number of structures; the behavior of the variogram model near the origin; and the specification of anisotropic features. Although the spatial variability model will change depending on the estimator and available data, it should be compatible with accepted geologic knowledge. For example, the modeled anisotropies should be consistent with the spatial distribution of known geologic controls, and the variances and ranges of the models should be consistent with the overall variability observed in the data.

Geologic variables have some degree of spatial correlation. The challenges often encountered when quantifying the spatial correlation lie with the inadequacy of the data being used, inadequate definition of estimation domains, or use of estimators that are less robust with respect to skewed data. These challenges are discussed in detail in later chapters.

1.3.4 Geologic and Mining Dilution

In-situ and *recoverable* resources must be differentiated. The precise definition of recoverable varies in different parts of the world. In general, the term refers to mineralization that can be recovered and processed by mining. Any resource evaluation, in order for it to become the basis for an economic evaluation, has to be recoverable, and therefore include some dilution and ore loss. After applying constraints derived from the ability to economically mine the deposit, as well as all relevant types of dilution, the resource may become a reserve.

Some resource estimators advocate the estimation of purely geological in-situ resources, that is, an estimate of the resources that are to be found if a snapshot of the deposit at the same scale and level of detail as provided by the drill hole data and other geologic information could be taken. Thus, it would be a description of its true geologic nature, as it occurs at our scale of observation. This point of view assigns to the mining engineer and economic evaluator the task of converting the purely geologic resource into a minable reserve. This is required to realistically describe the economic potential of the deposit. In general, however, the geologist and geostatistician (resource evaluators) are better equipped to incorporate geologic dilution; otherwise, it may go uncharacterized or poorly modeled.

Mining is a large scale industrial operation; selection of large volumes is taking place over short times. Some mixing of waste with ore and ore with waste is inevitable. The failure to understand and properly estimate geologic dilution and lost ore explains most of the failures of resource estimates. Although some degree of error or uncertainty is expected, ignoring or mistreating knowledge of anticipated dilution is an invitation for disaster. An interesting discussion in layman terms about this issue can be found in Noble (1993). In the context of using a block model to estimate resources, the basic types of dilution often encountered can be summarized as:

1. Internal dilution, related to the use of small size composites to estimate large blocks, also called the volume-variance effect. The more mixing of high and low grades within the block, the more important this effect will be, as is common for example with gold mineralization.
2. The geologic (or in-situ) contact dilution, related to the mixtures of different estimation domains within blocks. One reason for grade profile changes is the existence of different geologic and mineralization domains. Mixing of grades will occur when mining near to or at contacts.
3. The operational mining dilution that occurs at the time of mining. The blasting of the rock is an important factor, since material shifts position. The loading operation is also a source of dilution and ore loss since the loader is never able to precisely dig to the exact ore limits.

An understanding of the information effect is also required. The long-term block model is not used for final selection of ore and waste. Rather, a different model is used to select ore from waste that uses much more closely-spaced data available at the time of mining. In an open pit mine the mineral boundaries and the quality are predicted using closely spaced data. The information at the time of resource estimation is quite different than at the time of mining, for which estimates will be much better.

1.3.5 Recoverable Resources: Estimation

The importance of calculating recoverable resources and reserves was recognized early on in geostatistics (Matheron 1962, 1963), but it was M. David's early work (1977) that demonstrated the practical significance of estimating recoverable reserves, while Journel and Huijbregts (1978) provided the theoretical and practical foundations for the most common methods used to estimate at different volumes.

Block model resources estimated from exploration or development drill holes (long-term models) and mine production predictions (short-term models) may show significant discrepancies. The discrepancies are even larger when compared to actual production figures which may or may not be reliable. It is desirable to minimize these discrepancies for evaluation and planning purposes. It has been shown that incorrect accounting for the volume of prediction (the volume-variance effect) is a major contributor to the discrepancies usually encountered.

The resource model contains blocks with dimensions that should relate to the spacing of the data, hopefully determined based on the quantity of information available to predict grades. Block sizes may be larger than the selective mining unit (SMU) of the operation. The smoothing effect of kriging will generally result in a grade distribution that does not match the distribution of grade of the SMUs. In addition, in-pit selection is not perfect. The grade-tonnage predictions based on blast holes may need to be corrected for unplanned dilution and other errors of estimation in the short-term model.

An integrated approach to predicting reserves and mine performance is required for more accurate predictions. Specifically, the volume-variance relationship, the selectivity of the mining operation, planned dilution and ore loss must be accounted for. Additionally, incorporating an allowance for unplanned dilution at the time of mining is reasonable.

The traditional estimation techniques provide limited flexibility to account for these factors. The estimation of recoverable resources is based on limited information about the SMU distribution of grades. There are a number of methods and techniques that help estimate point distributions, but relatively little research has been done to develop robust methods for estimating block distributions. It is a difficult task, since little is known a-priori about the SMU distribution. An important option available is the use of conditional simulation models to resolve the issues related to recoverable resources.

1.3.6 Recoverable Resources: Simulation

The traditional approach to block modeling is to estimate a single value in each block of the model, obtaining the best possible prediction in some statistical sense. This estimation can be done using non-geostatistical methods, or more commonly, some form of kriging. Although there is a need for a single estimate in each block, there are some important shortcomings in attaching only the estimated value to each block.

An alternative approach to resource evaluation is the use of conditional simulation that provides a set of possible values for each block, which represent a measure of uncertainty. The idea is to obtain a number of simulated realizations that reproduce the histogram and the variogram of the original drill hole information. The realizations are built on a fine grid. Reproducing or honoring the histogram means that the realizations will correctly represent the proportion of high and low values, the spatial complexity of the orebody, the connectivity of high and low values, and the overall grade continuity in three dimensions. These characteristics of the mineralization are important aspects that play a significant role in designing, planning, and scheduling a mining operation.

A number of issues have to be adequately resolved for the realizations to be representative of the grades of the deposit. These include, among others, choosing among several simulation techniques available, such as Sequential Gaussian (Isaaks 1990), Sequential Indicator (Alabert 1987), or others. Also, decisions about grid size, conditioning data, search neighborhoods, and treatment of high grade values must be made. It is a similar process to developing a kriging block model. Some discussions about practical implementations can be found in Deutsch and Journel (1997) and Goovaerts (1997), among others.

When a number of these realizations have been created and checked, then, for each node defined in the grid, there will be a corresponding number of different grades available. This set of multiple grades is a model of uncertainty for that node. These simulated points can be re-blocked to any block size desired such as the Selective Mining Unit SMU size of the operation. These results are used further by mining engineers.

Important parameters can be obtained from the distributions of local uncertainty such as the mean, median, and probability of exceeding of exceeding a specified cutoff grade. Therefore, the information provided by a simulation model is significantly more complete than the single estimate provided by an estimated block model. The simulation models can provide recoverable resources for any selectivity by re-blocking the simulated grades to the chosen SMU block size. It is likely that, in due time, simulation models will replace estimated block models, since they not only provide a single estimate, but also a full range of possible values.

1.3.7 Validation and Reconciliation

Checking resource models involves several steps and requires a significant amount of time and effort. There are two basic types of checks to be done: graphical and statistical.

Graphical checks involve 3-D visualization and plotting the estimated values on sections and plans. Every estimated block grade should be explained by the data surrounding it and the modeling parameters and method used. Although these graphical checks can be performed on computer screens, it is often worthwhile to have a hardcopy set of maps because of the level of detail required and the important record-keeping and audit trails. Unfortunately, this practice is disappearing, as some operations do not take the time to produce sets of geological sections and plans views on paper.

Statistical checks are both global (large scale or deposit-wide) and local (block-wise or by smaller volumes, such as monthly production volumes). The checking, validation, and reconciliation procedures should ensure the internal consistency of the model, as well as reproduction of past production if available. Some of the more basic checks are:

- The global average of the model should match the average of the declustered data distribution. This check needs to be performed for each estimation domain.
- The smoothing of the distribution of the block model grades: the comparison with respect to the predicted (SMU) grade distributions should be reasonable. If the predicted SMU and block model grade-tonnage curves are very different, it is likely that the block model has incorporated too much or too little dilution.
- The spatial and statistical relationships between the modeled variables must correspond to the relationships observed in the original data set.
- A resource model should be constructed using an alternative method. The results and differences should be as expected, given the characteristics of each method.
- The estimates should be compared to previous estimates. This should be done cautiously and considering the differences in data quantity and quality, as well as the methodology used for the different resource estimate.
- The estimates should be compared to all available historical production data. Ideally, resource models should predict past production. This provides some indication that the block model may also predict future mining.

Reconciliation against past production should be done based on pre-defined volumes of interest and according to specified error acceptance criteria. Additionally, production can provide an initial indication of the expected uncertainty of the resource model. This expected uncertainty should be expressed in the classical form of *within x% confidence limit p% of the time*.

Production information should be used with great care. Oftentimes, tonnages and grades reported by the processing plant do not adequately represent true mill feed (head) tonnages and grades, that is, the material delivered by the mine. Rather, they may be influenced by plant performance parameters, which will bias the comparisons with the head grades and tonnages reported by the mine. The implication is that reliable head tonnages and grade information are best obtained from direct sampling of the material delivered at the entrance of the plant. In some cases these comparisons may not be possible due to the characteristics of the operation such as extensive stockpiling or lack of reliable mill feed information. Often, only very general statements can be made about the quality of the reconciliation data.

1.3.8 Resource Classification

The purpose of classifying resources is to provide a global confidence assessment to the project's stakeholders including mining partners, stockholders, and financial institutions investing in the project. There are several resource and reserve classification systems used by different government agencies around the world. Most of them share in their main characteristics and objectives.

The assessment of confidence is critical for project development since sufficient resources and reserves must be known with enough confidence to be considered assets. For operating mines, continued confidence in future long-term production is also important in providing shareholder value and supporting long-term planning.

The terminology used in most guidelines for classification is purposefully vague. They must be applicable to many different types of deposits, locations and mining methods. The guidelines do not prescribe specific methodology for quantifying uncertainty or risk. Rather, there is increased reliance on the judgment of the resource estimator, formalized through the concept of a competent or qualified person. A common basis for comparison is therefore difficult to achieve, since the wording may have different meaning under different circumstances, and depends on the individuals involved. A possible solution is to attempt to describe confidence in traditional statistical terms, and as a function of production units. There is an industry trend towards using a statistical description of uncertainty to supplement traditional classification criteria.

The confidence assessment required by the shareholders of a mining project is generally global, and mostly concerned with long-term performance. This is different from the shorter-term mining risk assessment that engineers need in the day-to-day operation of the mine. Unfortunately, a global confidence assessment is frequently also used as a local measure of uncertainty, which often leads to unreasonable expectations in the resource model. Current practice for resource classification includes different methods that have conceptual similarities. Some common ones are:

- Using the number of drill holes and samples near each block is geometric in nature and easy to explain, although it frequently tends to be simplistic in its implementation.
- The kriging variance provides an index of data configuration (Chap. 8), that is, a measure of how well each block in the model is informed at the time of estimation.
- Using different search radii to estimate blocks in a stepwise process, while keeping track of when the blocks get an estimated value. The more information is used to obtain an estimate, the more certain it will be.
- Deciding according to geologic criteria what drill hole grid spacing is required for the resource to belong to a category (measured, indicated, or inferred), and then searching throughout the deposit for that nominal grid spacing, thus classifying the different areas of the deposit.

Purely geometric criteria could be supplemented with conventional statistical criteria, that is, defining the expected grade and a corresponding range of possible grades around it. For example, measured resources may be defined as those predicted to be known ± 15 %, 90 % of the time for a volume equivalent to 3 months production. The model (numerical or subjective) used to come up with such a statement is most important to the effectiveness of the classification scheme.

There are shortcomings and pitfalls in the practice of resource classification. Many of these can be resolved with a defendable model of uncertainty based on geostatistical simulation. Inevitably, the process of classifying resources depends on the circumstances and conditions of the mining project being assessed in addition to purely geologic conditions and technical issues. Nevertheless, in all cases, the classification must be defendable by the professional that signs off on the resource model.

1.3.9 Optimal Drill Hole Spacing

Drill hole spacing should be optimal for a given cost-benefit analysis, which is dependent on the project development stage. New drill holes must reduce the uncertainty of the resources to a tolerable, pre-defined level, as required for project advancement.

A cost-benefit analysis of potential new drill holes requires assessing the benefit of decreasing the uncertainty of the resource model by a given amount. This amounts to quantifying the value of new information. If the consequences of errors in the resource estimates can be defined and quantified, then it is feasible to use simulated realizations to determine the economic consequences of uncertainty. This can be further refined by applying existing mine plans to the simulation models, such that, for a specific mine plan, an evaluation of the impact of new drilling on recovered reserves can be made.

In practice, this type of analysis is based on production volumes, such as metal sold in a month. If the parameters that describe metallurgical plant performance are known, then the uncertainty of the tonnages and grades fed to the mill can be directly linked to the risk of not achieving the expected production plan.

The typical question asked by the project development manager is "how many drill holes do I need?" The answer to this question requires a definition of the objectives of the new drilling in terms of uncertainty. Then, the applicable optimality criteria can be developed and the value of new drilling can be assessed. This could be expressed in dollar values, in terms of uncertainty and risk reduction, or in terms of reduction of cash flow and net present value (NPV) risk.

1.3.10 Medium- and Short-term Models

Medium- and short-term models are auxiliary models used to improve the local estimation of the long-term resources model. These are reserve models that are used in an operating mine for production purposes. Medium- and short-term models are used to improve the estimation of relatively small volumes of the deposit. This is useful because mine operations plan on smaller, shorter-term volumes. The definition of what is long-, medium-, and short-term varies from one operation to another; however, common use of the terms suggest that long-term refers to production periods of a year or longer, while medium-term refers to three to 6 months production, and short-term implying 1 month production or less. The periods chosen will be related to the budget and forecast cycles of the operation.

At most medium to large mining operations there is a yearly budget that updates the material movement and corresponding expected cash flows of the original long-term mine plan. It provides a cash flow prediction for the following year. Additionally, this budget is itself updated by a short-term forecast, usually done on a semi-annual, quarterly, or monthly basis, depending on the characteristics of the operation.

The update of the existing long-term model is accomplished by incorporating infill drilling and production information. Since this work is to be performed within a production environment, the procedures and methods used in updating the resource model are constrained by time and human resources. The definition of the most appropriate and practical methodology to update the geological and grade models can become a significant challenge.

1.3.11 Grade Control

Grade control is an important task performed at the mine on a daily basis. It is a basic, economic decision that selects the destination of each parcel of material mined. Mistakes at this stage are costly, irreversible, and can be measured in terms of cash flow losses and increased operational costs.

Grade control models are based on a large number of samples. In underground mines, production data is usually a series of tightly drilled holes, channel samples, or short holes to test production stopes. In an open pit environment, blast holes samples are obtained on closely spaced grids, according to blasting requirements. Less frequently, grade control drilling is performed separate from blast hole drilling, for example using dedicated reverse circulation (RC) drilling. In some geologic settings, surface tranches and channel samples are used as well.

Production samples are used to select ore from waste, and are affected by several sampling issues. Often, blast hole samples are not as reliable as samples obtained from exploration or RC drill holes. This is explained by a combination of drilling and field sampling methods. Sometimes, the large quantity of samples available will tend to minimize the impact of the error of a single blast hole sample.

Geologic variables are mapped in the pit or stopes, but are not always used in production control. Procedures for extracting some benefit from the local geology mapped should be implemented. The goal is to find practical ways of mapping and quickly processing geological information. The typical turnaround time for a grade control model in an open pit is 24–48 h.

Conventional grade control methods include defining grade outlines and using inverse distance, polygonal estimation, or more commonly kriging of blast hole grades. These methods do not account for the uncertainty in prediction. Alternatively, simulation of multiple realizations provides the basis for different optimization algorithms, such as the minimum-loss/maximum profit method.

In general, improvements from the simulation-based methods are evident in more erratic grade distributions and in more marginal mixed ore-type zones. More complicated grade control scenarios, such as those including multiple processing options and stockpiling, will also lend themselves to optimization through simulation based methods.

1.4 Historical Perspective

Hand-calculated sectional estimates continue to have a place in resource and reserve estimation. They have the advantages of directly accounting for expert geological interpretation and providing a first order approximation; however, they also tend to be optimistic with respect to continuity of the mineralization and the grade that can be achieved. Inverse distance and nearest-neighbor methods became popular in the early days of computer-aided mapping. The computer was used to mimic what was done by hand calculations, but hopefully faster. The implementation aspects of these techniques evolved as more sophisticated computer tools became available.

Mineral resource modeling evolved further with advances in drilling and assaying techniques, and with greater awareness of the possible pitfalls related to sample preparation and analysis. Methods used for geologic interpretation and modeling also evolved, mostly through the section-by-section interpretation and into three-dimensional modeling (wireframes and solids modeling for visualization). The occasional use of three-dimensional hand-made models was made common with the availability of computers.

Grade estimation techniques have evolved through the years, beginning with early geostatistics (Sichel 1952; Krige 1951; Matheron 1962, 1963) that attempt to predict single values into blocks. Advanced versions of these techniques are pervading industry practice and are the most commonly used methods.

The estimation of probability functions developed next, although using the same basic linear regression tools. Assumptions about statistical properties and variable transformations led to the development of probabilistic estimation of a distribution of possible values for any given block.

In more recent years the use of simulation for modeling uncertainty has become important. Geological processes have important patterns and structure, but also have uncertainty due to the chaotic nature of the processes. Characterizing the natural heterogeneity and the uncertainty that results from incomplete sampling is an important goal of mineral resource estimation.

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