Introduction to Mining Geostatistics

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Below is a quick review of the many geostatistical tools available to geoscientists nowadays, as well as a non-exhaustive list of typical fields of application in the Mining Industry.

Geostatistical tools

Geostatistics, in combination with other statistical methods, offers a wide range of mathematical tools that can be used to analyze, model, provide estimates and assess uncertainties, for different types of spatial features – e.g. grades or geological facies –

- **Data Mining**

  Analysing in details the statistics and spatial correlation of the available data is always the key step of a geostatistical approach. For this purpose one can use the following tools:

  - Exploratory Spatial Data Analysis (ESDA) consists in exploring the classical statistics as well as spatial statistics of one or several variables simultaneously, by means of Histograms, Cross-plots, QQ-plots, Variograms, etc. Linking these statistical graphs dynamically with data basemaps enables to further explore the data and assess the homogeneity of a population, the presence of outliers, etc.
    Variogram maps often help in finding the main directions of anisotropy of a phenomenon, while classical Experimental Variograms or Covariances are typically used to measure the spatial variability of the phenomenon in various directions.
  - Principal Component Analysis (PCA) for multivariate statistical analysis.

- **Spatial modelling**

  Building a mathematical Model that fits with the spatial statistics – variograms / covariances – of one or several correlated variables, is the second step of a geostatistical approach. This spatial Model is based on the data itself, through the experimental curves, but also integrates additional knowledge on the variable – e.g. geological features - through the choices of the geoscientist when building the model.
  A Model may be monovariate or multivariate, and may be composed of one or more nested spatial structures – each of them with its own ranges, directions of anisotropy, etc. – It is therefore a single mathematical function that can describe either simple or complex spatial structures.
  The same Model can be used for different purposes such as local or global estimation, simulations for uncertainty assessment, etc.

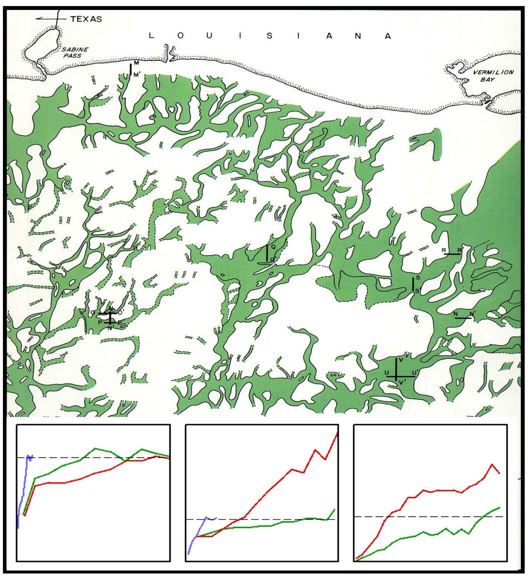

Figure 1:Directional Variograms in a Chanel environment

- **Linear methods of Estimation**

The spatial Model can be used for estimation of a variable, using Kriging, the well-known method named after Dr Krige. In fact there are various kriging methods depending of how many variables are involved in the data & Model, how the mean of data is considered, to name a few: Ordinary Kriging (OK), Simple Kriging (SK), and Cokriging.
Kriging can be applied on different supports – Point, Block, Polygon – and provides various numerical results at each target location:

- the Kriged Estimate, the most likely value of the variable on the Point, Block or Polygon
- the Standard Deviation of estimation, a measure of the local uncertainty attached to the estimate
- other auxiliary results – Slope Of Regression, Lagrange parameter, etc. –

Kriging is designed to be the Best Linear Unbiased Estimator - the difference between the true yet unknown values and the predicted values is equal to 0. "on average" – while simultaneaously providing the lowest variance of estimation.
However, like any other linear interpolator, Kriging is a smoothing process which does not reproduce the entire variability of the original phenomenon.

- **Distribution Modelling**

The experimental distribution – histogram - of a variable can be modelled by mathematical functions, such as the Anamorphosis function. This Model of distribution can be used to switch between the Raw variable and its Gaussian counterpart, which is required by most geostatistical methods – e.g simulations, non-linear geostatistics – The Anamorphosis function has also the advantage of being able to take into accout support effect & information effect. A first application is to predict the recovery of resources in relationship with the size of Selective Mining Units.

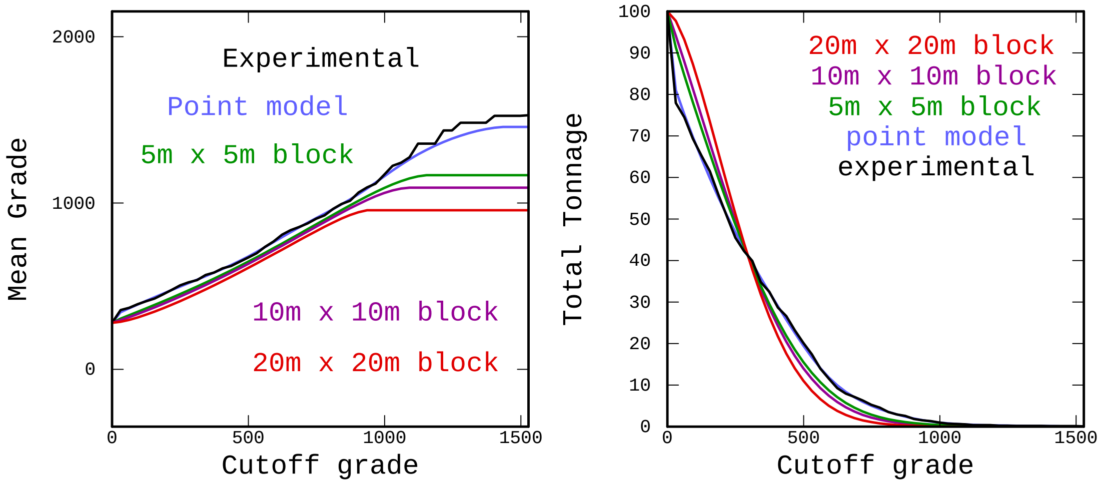

Figure 2. Selectivity Analysis through Tonnage & Mean Grade vs Cutoff Grade

- **Non-Linear methods of Estimation**

Since Kriging is a linear interpolator which cannot be applied to solve non-linear problems – e.g. estimation of tonnage & grade above a given cutoff, to assess Recoverable Resources - another family of estimation methods has been introduced to solve this problem. These non-linear methods are: Multiple Indicator Kriging (MIK), Median Indicator Kriging, Disjunctive Kriging (DK), Uniform Conditioning (UC), Lognormal Kriging & Service Variables.
Geostatistical simulations can also be used to tackle this very problem.

- **Simulations**
  - **for continuous variables**

  When one needs to assess the uncertainty attached to the prediction of a variable, or when realistic scenarii are required for post-processing algorithms – e.g simulation of production – the spatial Model can be used for simulation purpose rather than estimation.
  Unlike Kriging, Geostatistical Simulations are designed to generate a series of equiprobable realistic outcomes, each of these alternate models honoring the input data, the spatial Model as well as the data's distribution Model.
  There are different Simulation algorithms that can be applied to continuous variables – e.g grades – such as: Sequential Gaussian Simulations (SGS) & Turning Bands (TB).

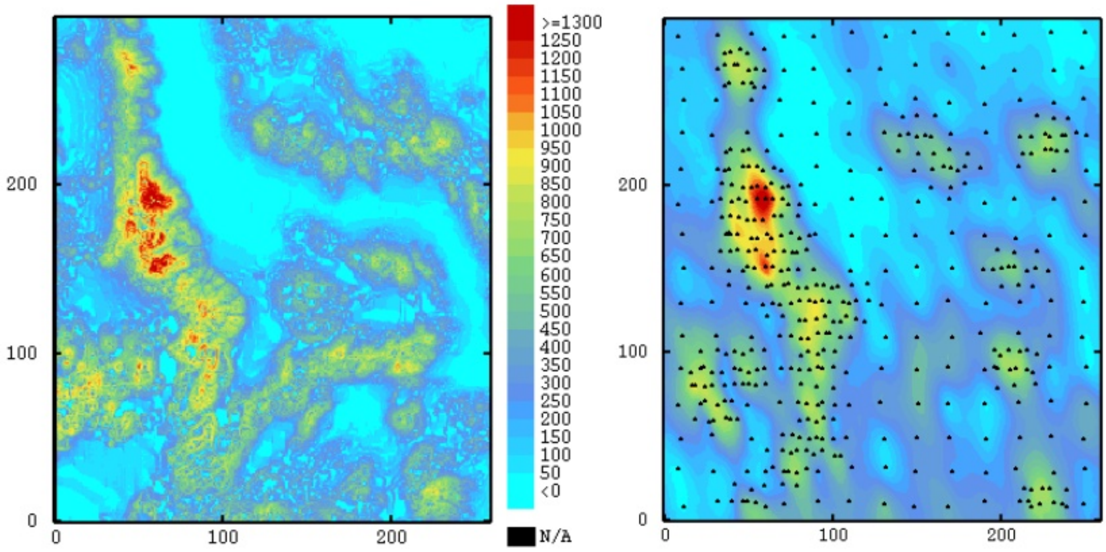

Figure 3. Kriging estimates cannot reproduce the original variability of the data

  - **for categorical variables – facies –**

  Other Geostatistical Simulation methods can be applied to categorical data – e.g. facies – in order to generated a series of alternate geological models for instance. The main facies simulation methods are: Sequential Indicator Simulations (SIS), Truncated Gaussian Simulations (TGS), Pluri Gaussian Simulations (PGS), Boolean Simulations and Object-based Simulations.

- **Other geostatistical methods**

  Although not so much applied in Mining, let us recall that other branches in geostatistics offer tools to improve the estimation or simulations of a variable by integrating auxiliary datasets - e.g seismic campaigns, remote sensing images, etc. – or to take into account Drifts for non-stationary phenomena. Let's just mention a few: Collocated Cokriging (CCK) & External Drift Kriging (EDK), Kriging with non-stationary models, Factorial Kriging.

Mining Applications

Here is a non-exhaustive list of common applications of geostatistics in the Mining Industry, and although presented from Exploration through Production, it is clearly not a "workflow" but merely a collection of usual applications - some tasks such as ESDA and spatial Modelling are obviously involved at all stages -

At the Exploration / Pre-feasibility stage

- In the early stage of exploration ESDA is a major task: it helps finding potential outliers, defining the groups of correlated variables, analysing statistics per domain, etc.
- variography itself helps in better understanding the geometrical configuration of the mineralization, which can be used as a guide for designing optimal drilling patterns.
- Kriging is used to build a first Block Model and estimate in-situ resources, as well as the Global Recoverable Resources of the prospect.
- Testing sampling strategies helps assessing the impact of sampling patterns on the reduction of uncertainty in the Resource Estimates.
- Facies Simulations – e.g. PluriGaussian – can be used for building a geological frame consistent with drillhole facies observations and the Geologist's conceptual model of the Orebody. Simulated facies could be used in the definition of domains, which in turn could be used to control the resource estimation process.

- **At the Feasibility stage**
  - ESDA & spatial Modelling, based on new input data
  - Evaluation of the impact of Selective Mining Unit (SMU) dimensions on the Reserves
  - Non-linear methods (MIK, DK, UC) are used to evaluate Reserves more precisely, based on a given SMU size and economic grade cut-off.
  - Geostatistical conditional Simulations may be used to assess the uncertainty associated with the Reserves Evaluation. The simulations provide a range of potential reserves for the orebody's Tonnage, Metal Quantity and Recovered Grade.
  - The estimation of local Confidence Intervals can be used for the Classification of Resources into Measured, Indicated & Inferred catergories.

- **In Production**
  - ESDA & spatial Modelling, based on new input data
  - Grade Control is improved by optimizing the pattern of production sampling
  - As the development goes on, SMU or Stope grades are re-evaluated with the local production sampling information. This updated grade model is used for short-term, medium-term or even long-term mine planning, to minimize the grade variability at the plant – e.g directly at mill head, or by stockpiling –
  - The actual grades sampled at the plant can also be compared with the grades predicted in the Resource Model for a reconciliation exercise.

Conclusion

Geostatistics, which originated in the Mining industry with the works of Dr Krige followed by the mathematical framework setup by Pr Matheron, is definitely widely used for Mineral Resource Evaluation and Production. It offers a wide range of analysis and stochastic modelling tools which have been developed over the years to solve practical problems, and it is now commonly used in combination with deterministic methods which are found in Geomodellers.

References

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