Comparison of Recoverable Reserves between Simulation and Kriging for Block Caving with Optimized Drawpoints

Efrain Ugarte, Yashar Pourrahimian, and Jeffery Boisvert
Mining Optimization Laboratory (MOL)
Center for Computational Geostatistics (CCG)
University of Alberta, Edmonton, Canada

Abstract

At present, it is well known that Kriging is the most popular geostatistical estimation technique in the mining industry. However, Sequential Gaussian Simulation keeps gaining more terrain in this important extractive industry. For instance, realizations have being used in different mining applications to solve specific issues for the operation, planning, and design of the mining projects. A potential field where simulation can be explored is the design for block caving, so that reliable results of minable resource is obtained. In the block caving, the constraints and parameters are numerous and the calculation of recoverable reserves tend to be very challenging. Nonetheless, this paper suggests a short guide to manage the Kriging and simulation block models generated by GSLIB and to process them into Gems-PCBC. The response results of tonnage, grade and profit based on the both techniques have been compared, and an interesting discussion about SGS advantages is given. The possible impacts that these results might cause in the economics of a block caving mines is also discussed. Regardless certain drawbacks, the methodology based on sequential Gaussian simulation to obtain the recoverable reserves is suggested.

1. Introduction

There are many detailed studies contrasting kriging and simulation for estimating recoverable resources and reserves. Nonetheless, the intention of this paper is not to repeat all that so far has been reviewed about these two types of techniques, neither to show in this document an underground mining approach related to block caving; that would be more extensive and more oriented to mining engineering. This paper basically explains the final results of the optimal minable reserves obtained within a commercial software by using previous numerical models generated with kriging and simulation, and the overall impact that these models could cause to the economics and to the evaluation of a block-caving project.

The beginning of the paper is dedicated to explain briefly about simulation and kriging, where certain studies regarding these geostatistical techniques are highlighted. The second part of this

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paper recommends a number of geostatistical programs that are used to perform block models, from the GSLIB catalog's software (Deutsch, C. V., & Journel, 1998) as well as the PCBC (Gems, Dassault Systemes) that is used to process these numerical models, so that the optimized recoverable resources can be calculated. Before the numerical models are processed, they first have to be imported into a commercial software specialized for block caving (PCBC-Gems). The last part of the paper includes a short explanation to obtain recoverable reserves by "all realizations all the time"; therefore, all the results obtained from all realizations are contrasted with the results given by ordinary kriging in terms of net value, tonnage, and grade. Figures and snapshots with setting of the mining parameters and runs, as well as, tables and plots with results are shown in this paper.

2. Simulation and Kriging

There are a good number of papers and theses that have been written about both kriging and simulation over the past years; these works include differences, advantages and disadvantages. For instance, the short paper wrote by B. Wilde and C. Deutsch in the CCG report, 2005, titled "the Comparison of Kriging and the Average of Simulated Realizations" is one of them. This interesting note shows several examples where the authors mention that "it is incorrect to assume that ordinary kriging is the same as the average of simulated realizations". Another interesting work is the study made by Deepak Bhandari, 2007, "Comparison of Recoverable Reserves Estimation Techniques"; his theses to obtain a Master of Science at University of Alberta. In his theses, Deepak performed a comparison of estimated values to reference values for kriging and SGS. He concluded that simulation removes the smoothing of grade that kriging usually generate, thus SGS has the capability of producing very high and very low values providing a very solid platform for decision making. Deepak, however, mentioned in his work that SGS possesses a small disadvantage that is related to the management of multiple realizations. This drawback used to make the mine design and planning more challenging. However, recent computational developments allow to improve the management of a reasonable number of realizations.

Many studies confirm that kriging is very popular and is referred to as "the Best Linear Unbiased Estimate"; this geostatistical technique is being used for decades in the mining industry despite the smoothing effect on grades (Cu) that it can be generated. In contrast, a great number of studies and research show that simulation is being used a lot and for many years on the hydrocarbon reservoir modeling, yet lesser in mining. Nonetheless, mining professionals have been given much more attention to this technique, thus SGS is gaining more space in this sector.

The main advantage of the simulated realizations is that they allow performing good uncertainty assessments. Furthermore, it is important to mention that advances in computational hardware, software, and intense research on simulation applications is making the use of this geostatistical technique commonplace (Deutsch, 2015). In fact, simulation has shown that it has a good potential to be applied in the mining industry.

3. Common Programs to Obtain Recoverable Resources

Here is listed the main programs that are used to obtain the kriged and simulated block models, so that the mineral reserve calculation can be performed. In addition, a brief explanation to generate the numerical models that is imported to third party software is made. The manipulation of these numerical models is performed within PCBC-Gems, thus the estimates of recoverable reserves for the block-caving mines are obtained.

First, several steps need to be conducted to produce a kriged block model that requires the usage of some programs from the GSLIB catalog (Deutsch & Journel, 1998). This detailed guide should contain a step-by-step procedure. However, this paper only includes an overall explanation to perform a kriging estimation, as shown in Fig 1.

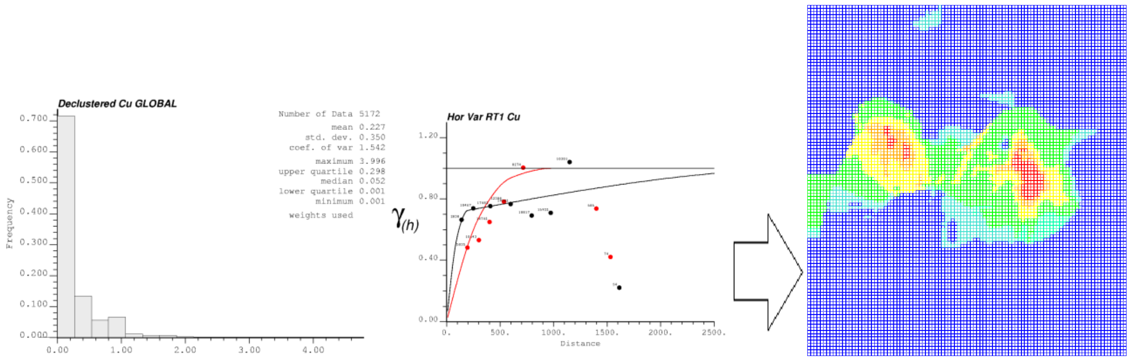

Fig 1. The generalized steps to generate a kriged block model with GSLIB programs

1. *Compositing:* This software was developed by D. S. F. Silva (2014). It calculates compositing using assay data of the format (ID FROM TO VAR1 … VARn). Notice that compositing is the starting point of any geostatistical estimation.
2. *HISTPLT:* This program has been written to generate some relevant univariate statistical summaries and show comprehensive histogram plots.
3. *GAMV:* The program is commonly used for irregularly spaced data, and the experimental semi-variogram is calculated.
4. *VMODEL:* This is a program for variogram fitting, and allow for fitting any number of variogram points with some nested spherical structures.
5. *kt3d:* The main program here is the 3-D kriging program (kt3d). This program performs kriging estimations on a grid, and also kt3d is helpful to conduct an efficient cross-validation before kriging or simulation is performed.

To create a number of conditional realizations of an input variable (Cu) and use the equally-probably numerical models in PCBC (transfer function) to yield the recoverable resources, it is necessary to replicate the steps presented by Leuangthong et al. (2004) where GSLIB programs are used. Notice that every step is linked to a specific GSLIB program. Some of them are already mentioned, above.

1. Composite data (Compositing) and generate histograms (HISTPLT) are also needed for simulation.
2. *DECLUS:* The program is used to obtain the declustering weights. This program provides an algorithm for generating 3D declustering weights for the composited data used in simulation
3. *NSCORE:* This program allows data transformation from original unit to the Gaussian units.
4. The *GAMV* and *VMODEL* are also used for simulation in order to fit an isotropic variogram with two nested spherical structures from the normal scored data.
5. *SGS:* The sequential Gaussian simulation program is one of the most commonly applied methods for simulation. This is the most important software at this section
6. *Histpltsim:* This is software for histogram reproducibility. It is important to mention that, the quality of the simulation model is checked by histogram and variogram reproducibility.

After the main GSLIB software are listed above, it worth to emphasize the step by step explanation to perform kriging and simulation is not very well detailed in this paper. The theses "Comparison of Recoverable Reserves Estimation Techniques" wrote by Deepak B. (2007) would be used as a guide. Fig 2 shows histogram, a fitted variogram and a kriging model. Declustering plot along with fitted variograms, and an example of the 40 realizations are displayed.

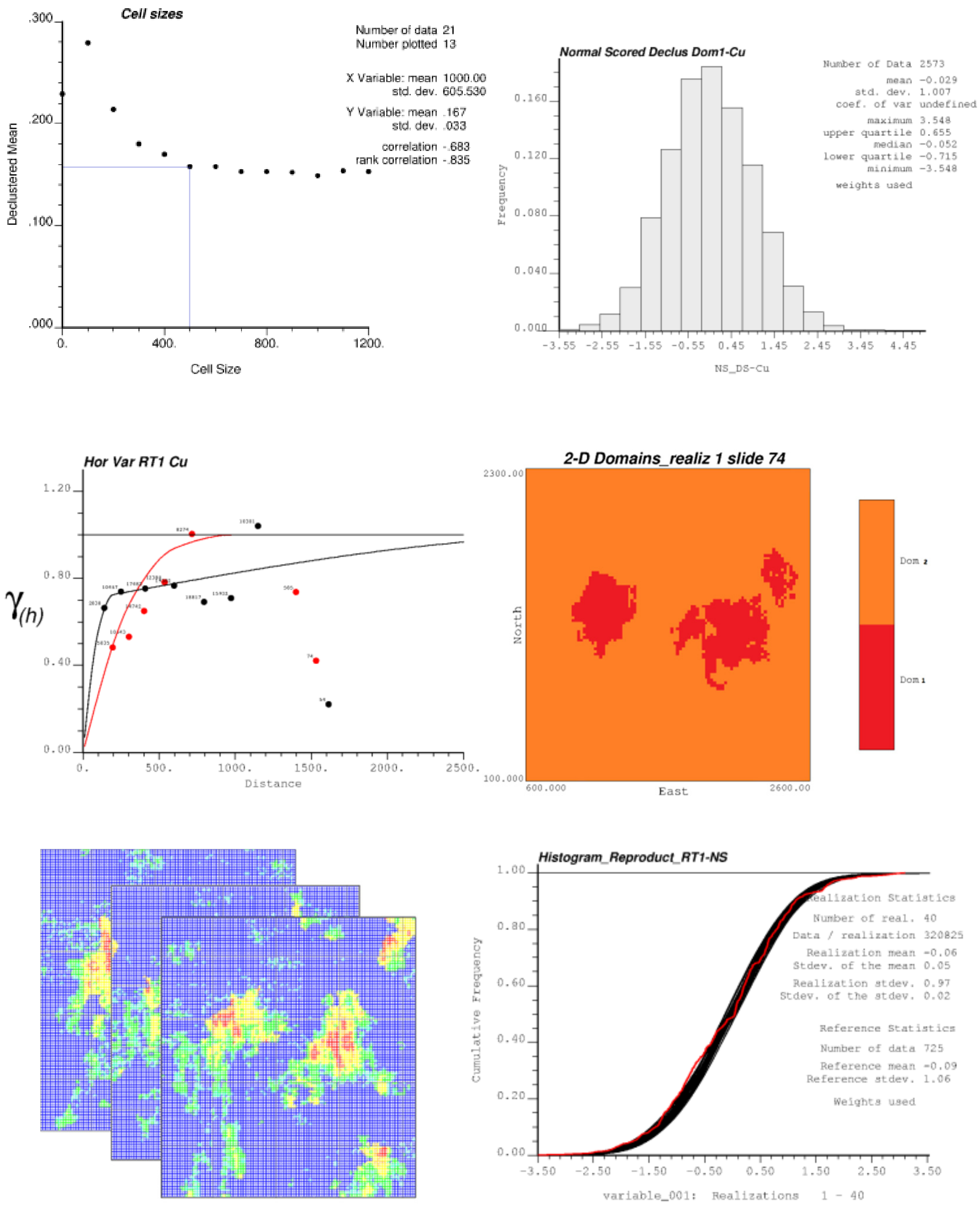

Fig 2. Main steps to generate a set of 40 realizations.

Once the kriged numerical model and the 40 realizations have been performed, they need to be imported into Gems. When each realization and kriging copper model is imported to this commercial software, each one of them is considered as an independent block model. Hence, forty-one block models are now ready to be processes within Gems-PCBC. Notice that these forty-one block models need to have lithology, density and percentage of fines before any further evaluation. These values have been previously calculated and imported to Gems, as well.

As mentioned above, Gems Software has a module called PCBC. This module is a specialized section for block caving. In PCBC, the block models, which are imported and set in Gems, are manipulated in order to perform the calculation of the recoverable reserves. Fig 3 shows two plots summarizing the PCBC routine to obtain the recoverable resources after the numerical models are imported and the layout is set. This paper does not pretend to show a complete procedure for using the PCBC module.

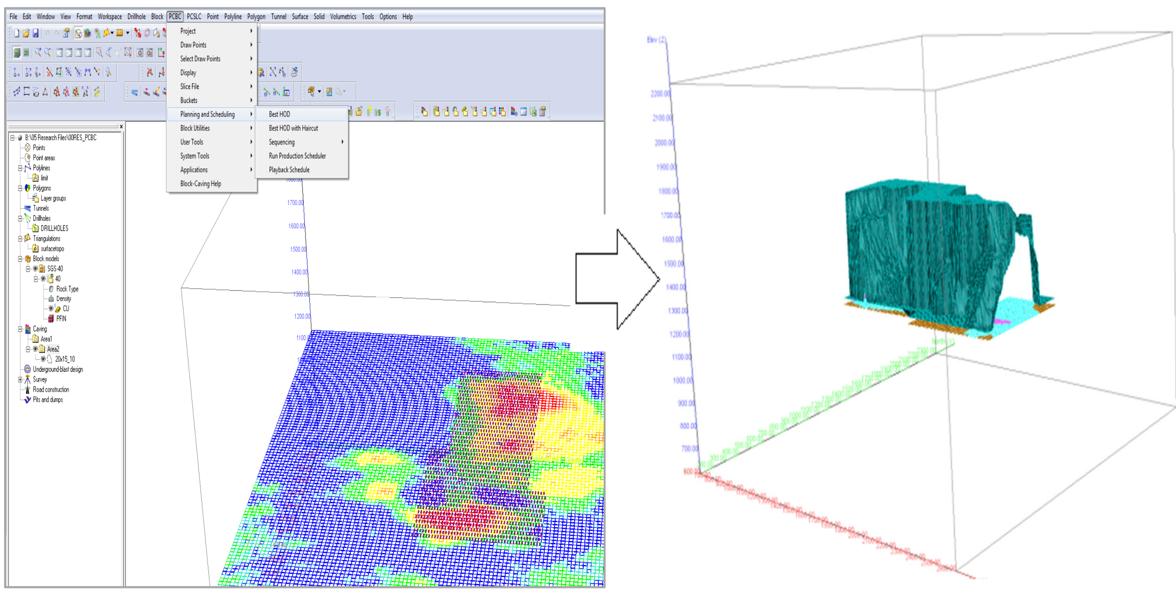

Fig 3. Summary of the PCBC work. From the imported block models through the recoverable reserves

Fig 4 shows relevant settings to generate the net value and the recoverable reserves within PCBC. These plots illustrate an overall idea about how the parameters and assumptions need to be completed inside the block-caving module of Gems.

The manipulation of these numerical models within PCBC is certainly the main part of this paper because the results that are obtained in this stage are relevant for our purpose of comparing the recoverable reserves based on Kriged block model against the recoverable reserves from the 40 realizations. Notice that the average of the 40 response values is compared to the response values of the kriged block model.

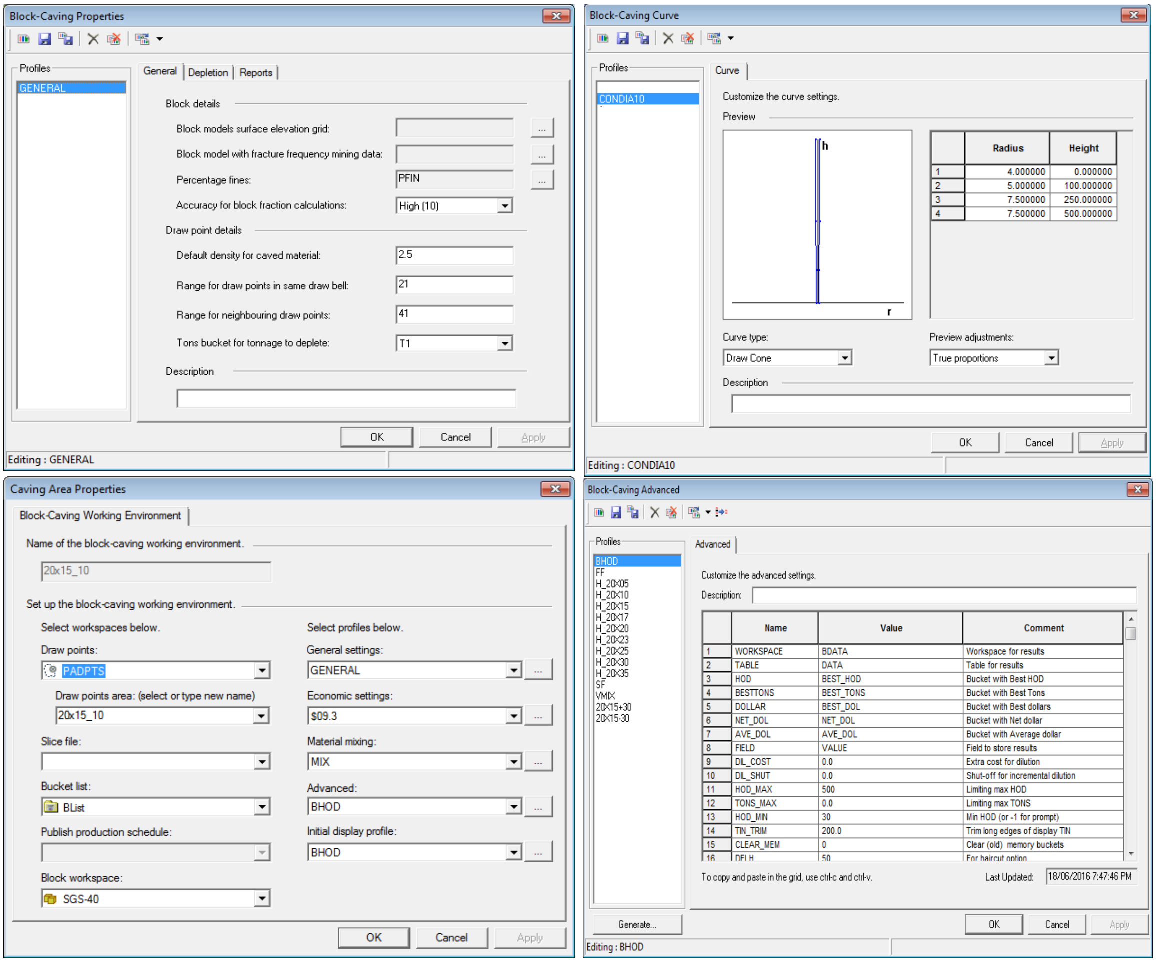

Fig 4. Snapshots of the PCBC panels with the setting to generate responses of reserves and net values

4. Compare Results from OK and SGS: Tonnage, Grade and Net Value(profit)

To compare the results of the optimized reserves, based on kriging against the results from simulation is essential to manipulate the numerical models with PCBC-Gems. Then, it is important to start choosing the layouts for the extraction level. They contain several parameters that need to be considered. A schematic plot is shown in Fig 5 where (A) is the spacing between drawpoint in a drawbell, also called brow to brow spacing, (B) is the spacing of the draw zones across minor Apex, (C) is spacing of draw zones across major Apex, (D) is the width of extraction drive and (E) is the distance between two extraction drifts (Ahmed, 2014). For the purpose of the study, a number of layouts are set in PCBC. Table 1 shows the three main layouts that are used in this work.

After the drawpoint spacing of each layout for the extraction level is set, additional block caving setting is performed in PCBC-Gems. Fig 4 shows the main panels that is filled out with assumptions and mining parameters. For instance, mining and development cost, density, percent of fines, drawcone radius, etc. Some mining assumptions can be seen in Table 2.

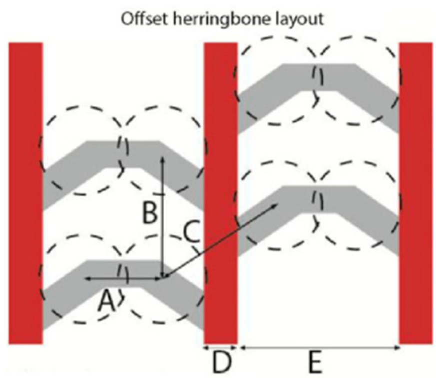

Fig 5. Scheme of the parameters of design in an extraction level (Ahmed, 2014).

Table 1. Drawpoint layouts used to find the optimal net value

Layout type (Herringbone)	Spacing across major pillar (m)	Spacing across minor pillar (m)	Observation
20x10_10	20	10	The distance between drawpoints within same bell is 10m
20x15_10	20	15	
20x20_10	20	20	

Table 2. Mining parameters and assumptions for PCBC.

Parameters & Assumptions	Value	Units	Description	References
% of Fines	30	%	Based on a model of fines	Diering, T., (2013)
Density	2.5	kg/cm^3	Average density for the orebody	Authors (2016)
HIZ	100	m	Height for interaction zone	Diering, T., (2013)
Swell factor	1.2	-	Stablished by experience	Authors (2016)
HOD_MAX	500	m	Maximum Height of Development	Diering, T., (2000)
HOD_MIN	30	m	Minimum Height of Development	Diering, T., (2000)
Discount Rate	0	%	It is assumed 0 % discount rate	Authors (2016)
Initial Elevation	1150	m	Initial Elevation of extraction	Get from Geovia info “Footprint Finder”
Draw cone radius	5	m	Based on fragment sizes	Laubscher D. (1994)
layout type	-	H	Herringbone is the layout type	Ahmed, H. et al.(2014)

The copper values of the 40 realizations as well as the copper values of the kriged model have been considered as the input variables. The Gems-PCBC is used as the transfer function of the simulation and kriging systems. The recoverable reserves and the net value are the response variables; they are in terms of tonnage and dollars respectively. In the Table 3, the tonnage results based on the simulated realizations are summarized and contrasted to the results obtained by processing the kriged block model.

For the kriged model, the maximum value of tonnage and grade are given for the extraction layout of 20×10_10 while the layout 20×15_10 shows the highest net value. In contrast, the SGS model show two scenarios. First, the mean of the 40 responses suggest that the maximum value of tonnage and grade is in the extraction layout of 20×10_10, and the highest net value is obtained from layout 20×15_10. The second scenario, shown in the Table 3, gives 40 equally probably results of the tonnage, grade and net value. Notice that the maximum possible tonnage is calculated within realization R=10 and the minimum possible tonnage is calculated within realization R=4. The results can be also used to perform further risk management, and to do decision making assessments.

The response results have been affected by the number of drawpoints, and consequently by the development cost. Fig 6 shows a plot where the averaged tonnage of the 40 realizations is contrasted with the tonnage and grade of optimized kriged model for the three chosen extraction layouts. The decrease on the tonnage is here directly related to the decrease of the number of drawpoints.

Table 3. Results of tonnage, grade and net value to compare the OK and SGS recoverable reserves

Extraction	Recoverable Reserves (Mt)			
Layout	Minimum- SGS	Maximum SGSim	Mean SGSim	Kriging
20x10_10	234 (R=40)	315 (R =10)	285	303
20x15_10	220 (R=9)	267 (R =36)	249	263
20x20_10	184 (R=4)	221 (R =7)	207	216
	Total Grade (Cu %)			
20x10_10	0.68 (R=7)	0.78(R =36)	0.72	0.72
20x15_10	0.60 (R =34)	0.69(R =36)	0.65	0.65
20x20_10	0.55 (R =3)	0.65(R =36)	0.61	0.61
	Net Value (million $)			
20x10_10	919(R =3)	1998(R =36)	1516	1650
20x15_10	1530(R =3)	2384 (R =5)	2046	2202
20x20_10	1581(R =3)	2256 (R =5)	1989	2125

Table 4 shows the layout of extraction 20×10_10 contains 4570 drawpoints. Therefore, the greatest amount of tonnage is expected to be extracted from this layout (Fig 7). However, the development cost is the highest. As a result, it causes the net value to be the lowest, among the three extraction layouts. Fig 7 also displays that the maximum net value possible is within the 20×15_10.

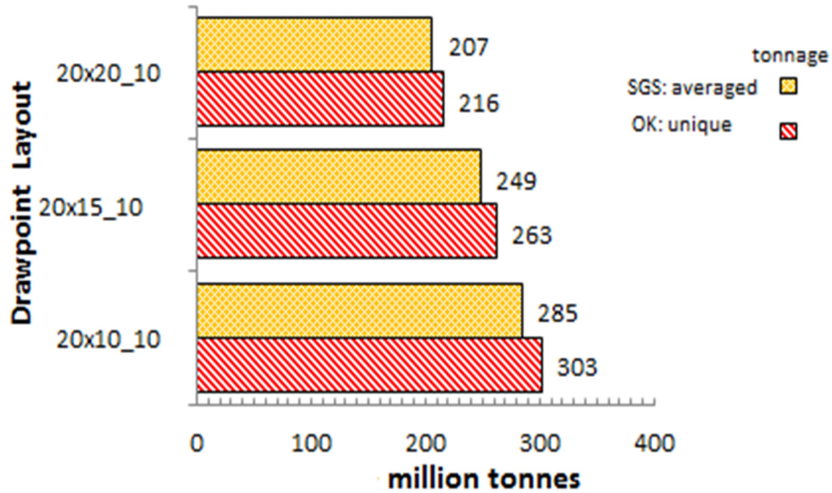

Fig 6. Tonnage (Mt) calculated within the three layouts of extraction

Table 4. Number of drawpoints and development cost for the three layouts

Block Cave Layout	# of Drawpoints	Development Cost ($/drawpoint)	Total development Cost ($M)
20×20_10	2296	150,000	344
20×15_10	3044	150,000	457
20×10_10	4570	150,000	686

Three response distributions (net values) of the simulated models are shown in Fig 8, in where the orange diamonds are the averages of the net values for each layout. These distributions are compared to three kriging responses that are displayed as three red circles. After a quick visual review, the distribution that appears to be the optimal is located within layout "20×15" for both OK and SGS.

Then the comparison of recoverable reserves between simulation and kriging for our block caving project is performed by using the layout with the optimized drawpoints. In other words, this calculation is conducted in the layout "20×15". A graphical representation of the comparison is illustrated in Fig 9. The Fig 9 generalized the process where the input models pass through a transfer function, which later will estimate the recoverable reserves from the block models generated by Kriging and simulation.

5. Results and Discussion

According to Table 3, the recoverable reserve that is estimated from the kriged model, with the optimal layout, is around 263 Mt with a grade of 0.65 % Cu. In contrast, the recoverable reserves that is estimated from the simulated models shows an average of 249 Mt, with an average grade of 0.65 % Cu.

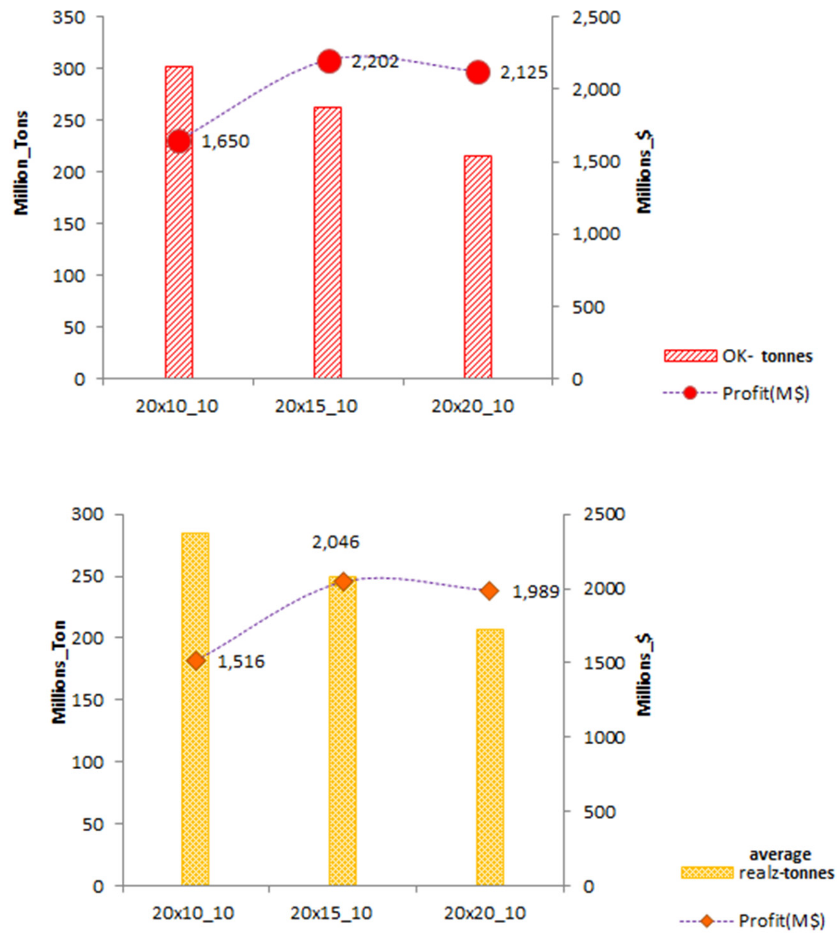

Fig 7. Optimized kriged tonnage and averaged simulated tonnage

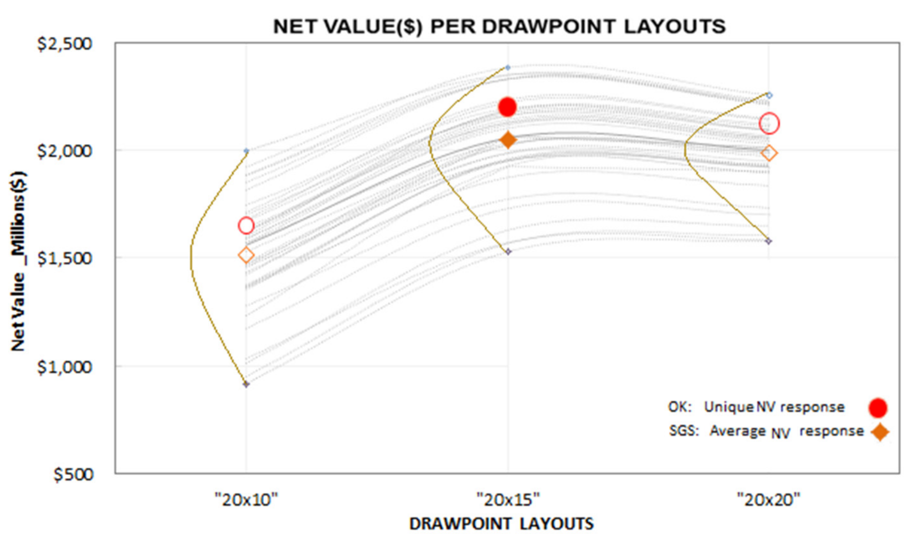

Fig 8. Three distributions of the Net-Value results ($M) based on kriged and simulation models

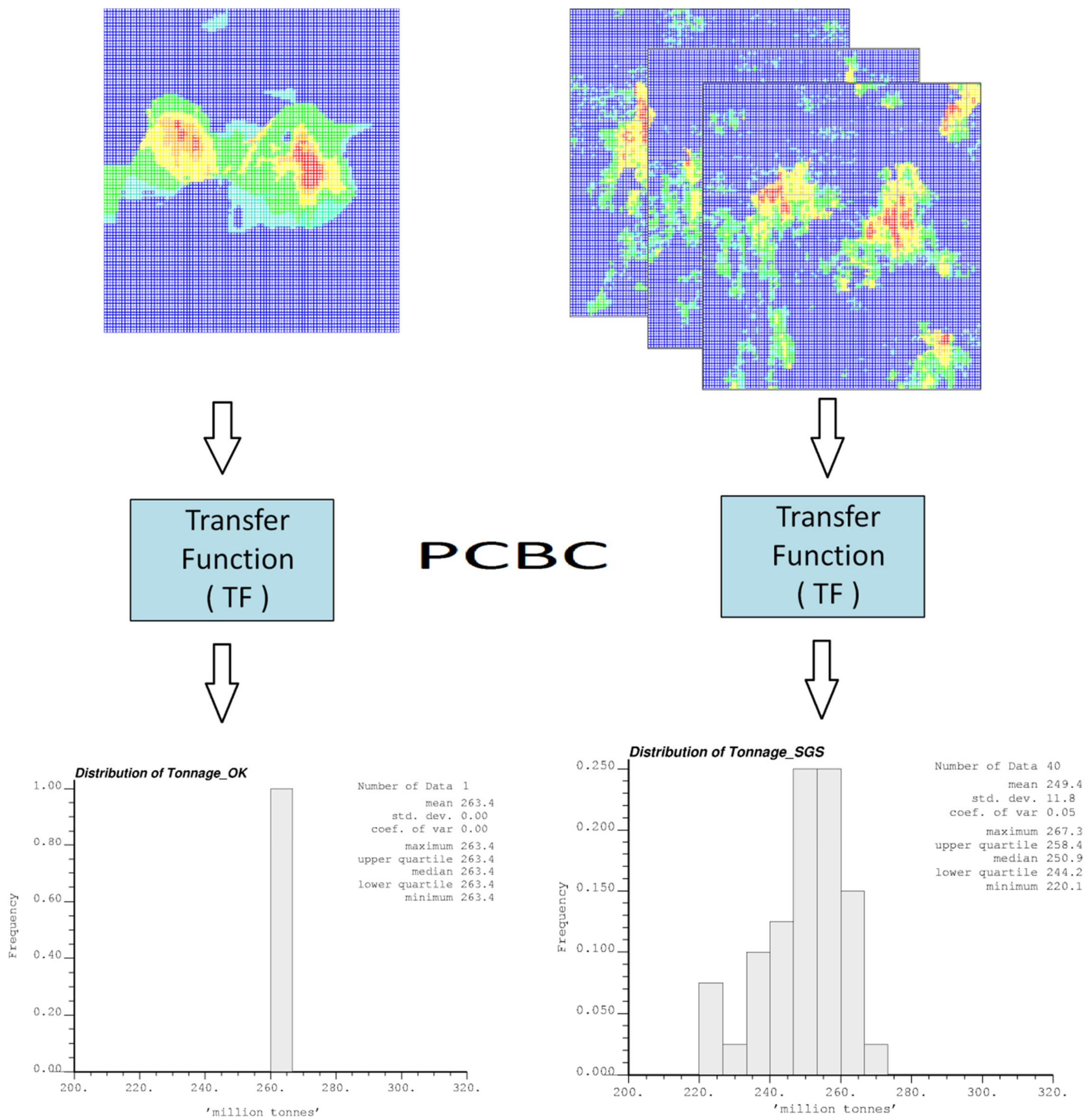

Fig 9. Comparison of recoverable reserves between simulation and kriging within the optimal layout

As it can be seen from the results and the histograms of the Fig 9, the smoothing effect of kriging is probably causing that the tonnages and net value to be greater than the averages of tonnage and net value from all 40 realizations. The usage of the response averages is highly recommended to get a trusted estimation of recoverable reserves (Clayton Deutsch, C. V., 2015). In other words, the average of the tonnages of copper that is generated by PCBC over the 40 realizations is much more reliable than a unique value given by PCBC over the kriging model. It worth to mention that, further uncertainty studies could be performed using these 40 response values. The assessments will certainly allow to evaluate risk and obtain a solid platform for decision making in this block caving project.

6. Conclusion

Even though kriging is widely use to estimate the recoverable resources in almost all types of mineral deposits, this paper illustrates some interesting ideas for using all realizations all the time in the block caving field. Then, using these equally probable models for the design of a block caving mine, and also in the estimation of minable reserves is here recommended. The reliable estimation of the mineral reserves is linked to the optimal layout of drawpoints at the extraction level. Then, it is important to remember that the optimal layout is highly relevant for any block caving mine, since this design has important effects in the evaluation of the economics of the project.

Despite the fact that the block caving design depends on many parameters and constraints and its evaluation is very challenging, an efficient extraction layout could be obtained by using a set of realizations. Managing a huge number of realizations is still a bit time consuming, hence the usage of 40 to 100 realizations is recommended. Moreover, hardware and software have been improving over the years. Therefore, the computer problems are not an issue anymore.

Overall, the comparison results of tonnage and grade as well as their profit based on kriging and realizations suggest that there is a potential opportunity to use SGS in the evaluation of block caving mines in order to obtain trusted estimations. However, additional uncertainty studies need to be developed in order to obtain a very solid floor for decision making.

7. References

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