Transfer of Geological Uncertainty through Mine Planning

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Uncertainty is always present in presence of sparse geological data. Geostatistical simulation algorithms are used to assess geological uncertainty. The generated realizations are equally probable and represent plausible geological outcomes. Long-term mine planning and the management of future cash flows are vital for surface mining operations. Traditionally the long-term mine plans are generated based on an estimated input geological block model. The most common estimation method used in industry is Kriging; however, Kriging results do not capture uncertainty and may be systematically biased. Mine plans that are generated based on one input block model fail to quantify the geological uncertainty and its impact on the future cash flows and production targets. A method is presented to transfer geological uncertainty into mine planning. First, Sequential Gaussian Simulation is used to generate fifty realizations of an oil sands deposit. An optimum final pit limits design is carried out for each SGS realization while fixing all other technical and economic input parameters. Afterwards, the long-term schedule of each final pit shell is generated. Uncertainty in the final pit outline, net present value, production targets, and the head grade are assessed and presented. The results show that there is significant uncertainty in the long-term production schedules. In addition, the long-term schedule based on one particular simulated ore body model is not optimal for other simulated geological models. The mine planning procedure is nonlinear and the mine plan generated based on the Kriging estimate is not the expected result from all of the simulated realizations. The probability of each block being extracted in each planning period and the probability that the block would be treated as ore or waste in the respective period are calculated and used to assist in long range planning.

Introduction

Mining planning is a process to find a feasible block extraction schedule which maximizes net present value (NPV) and is one of the critical processes in the mining engineering. Also there are some technical, financial and environmental constraints that should be considered. The uncertainty of ore grade may cause some shortfalls at the designed production and discrepancies between planning expectations and actual production. Vallee (2000) reported that 60% of the mines surveyed had 70% less production than designed capacity in the early years. Others (e.g., Rossi and Parker, 1994) reported shortfalls against predictions of mine production in later stages of production. Traditional production scheduling methods which do not consider the risk of not meeting production targets caused by grade variability, cannot produce optimal results. Rendu 2002 and Osanloo et al 2007 have explained the uncertainty assessment and algorithms in long-term mine planning. The negative effects of grade uncertainty in optimizing open pit mine design are articulated in Smith and Dimitrakopoulos (1999), Dimitrakopoulos et al. (2002) and Godoy and Dimitrakopoulos (2004) . Most of these methods are not efficient because they assess risk in a schedule, and do not produce optimal scheduling solutions in the presence of uncertainty. In addition, these efforts do not consider multi-element deposits with complex ore quality constraints, such as nickel laterites, iron ore or magnesium deposits. Furthermore, dealing with orebody uncertainty needs to consider issues of equipment access and mobility in the related “stochastic” optimization formulations. Dimitrakopoulos and Ramazan (2003) present a risk-based production-scheduling formulation for complex, multi-element deposits, which was based on expected block grades and probabilities of grades being above required cutoffs. They use jointly simulated models to get these values, but these values come from local distribution without considering jointly uncertainty and at multi-Gaussian framework, kriging can fully characterized local distribution.

Methodology

The concepts and results will be illustrated through a case study corresponding to an oil sands deposit in Fort McMurray, Alberta. In order to quantify the geological uncertainty transferred into the mine plans the following steps have been followed:

Geostatistical Modeling

There are geostatistical simulation methods that are widely used to assess uncertainty in GEO-data. All of these realizations are equal probable and can be consider as a plausible representative of geological complexity. Choosing one or some of these realizations will not be objective to fair uncertainty assessment. It is important to use sufficient number of realizations to get a robust mine plan. We have followed the steps presented by Leuangthong et al. (2004) in geostatistical modeling of oil sand deposits using GSLIB (Deutsch and Journel, 1998) software catalog to create conditional simulated realizations. The name of the programs used in the following paragraphs all refer to GSLIB programs (Deutsch and Journel, 1998). Stages presented by Leuangthong et al. (2004) are:

1. Analyze of correlation structure. This investigates whether a transformation of the vertical coordinate system is required, in order to determine the true continuity structure of the deposit. Determination of the correct grid is dependent on the correlation grid that yields the maximum horizontal continuity.
2. Decluster drillhole data distribution. The relevant statistics must be deemed representative of the deposit prior to modeling. Any or a combination of cell, nearest neighbour and/or declustering by kriging weights may be employed to determine the summary statistics that are representative of the field. We used the DECLUS program to get declustering weights whereby values in areas/cells with more data receive less weight than those in sparsely sampled areas. The DECLUS program provides an algorithm for determining 3D declustering weights in cases where the clusters are known to be clustered preferentially in either high or low valued-areas.
3. Model spatial continuity of the bitumen grade using variograms, which is the common spatial measure of continuity that shows the variability of grades with distance. We transferred data into normal scores using the NSCORE program; afterwards we calculated the directional experimental variograms using the GAMV program. VMODEL program was used to fit an anisotropic variogram with two nested spherical structures. The Azimuths of major and minor directions were 50 and 140 degrees. Figure 1 shows the location map of boreholes and Figure 2 shows histogram of bitumen grades in mass percent. Figure 3 shows the experimental and fitted variogram model in major, minor and vertical directions. The block defined bellow is chosen to model the domain. Perform estimation and cross validation using kriging as checks against simulation results. Cross validation using kriging provides a quality control check on the estimation (and also simulation) parameters. We used a large block with the origin coordinates of X = 146000m, Y = 251000m, and Z=190m to model the domain. The small blocks represent a volume of rock equal to 50 m×50 m×10 m. The model contains 331,200 blocks that makes a model framework with dimensions of 120X ×120Y×23Z. We used Ordinary Kriging to estimate the bitumen grade at each block location. Kriging is widely accepted in the mining industry and yields a map of the large Figure 3 expected value of conditional distribution at each location, E-type result is the mean value of simulation values at each location. Both of Ordinary Kriging and E-type estimation were done at the original unit. The shape of variogram and histograms were not produced with these two methods. Figure 4 illustrates the plan view of the Kriged model at the elevation 290m. Also, Figure 5 shows the E-type estimation for fifty realizations. There are more blocks below the 6% bitumen cutoff represented by blue color in the kriged model (Figure) compared against the E-type model (Figure 5).

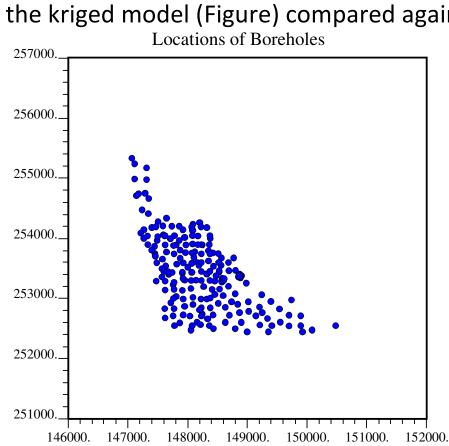


Figure 1. Location map of boreholes, units in meters.

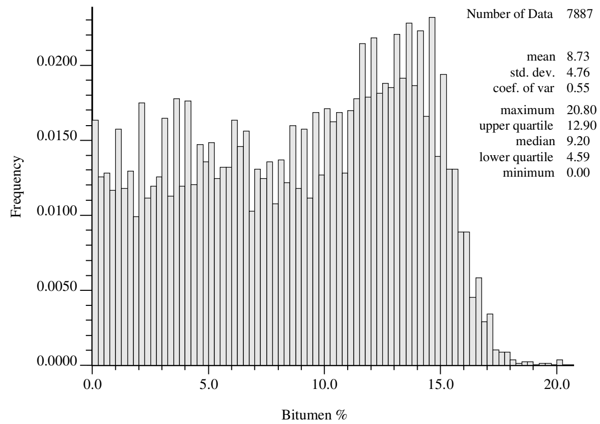


Figure 2. Histogram of bitumen grade (%mass).

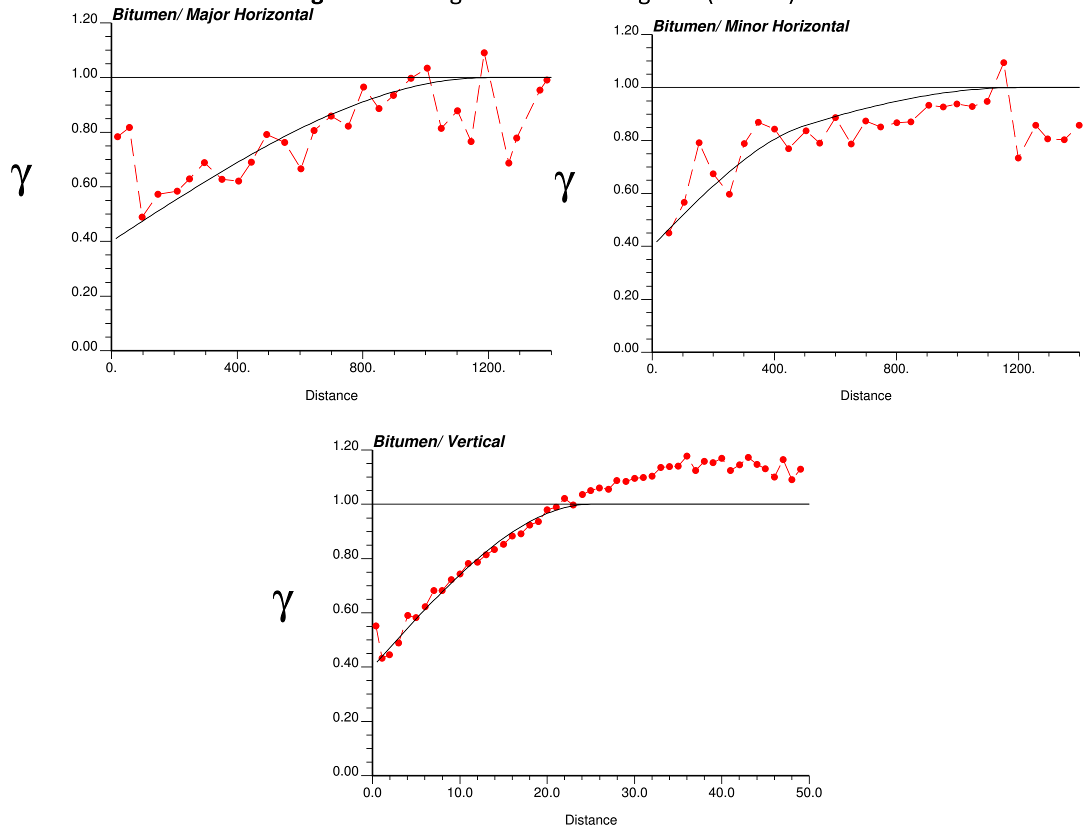


Figure 3. Experimental directional variograms (red dots) and the fitted variogram models (dash lines), distance units in meters.

4. Generate multiple realizations of bitumen grade using Sequential Gaussian Simulation (SGS) (Isaaks, 1990), this method is the means of constructing uncertainty models of bitumen grades. SGS is by far one of the most commonly applied geostatistical simulation algorithm applied in the natural resources sector. It has been extensively validated and provides a measure of local and global uncertainty, which is not afforded from Kriging. We used the SGSIM program to simulate fifty conditional realizations using the variogram model presented in Figure 3. Figure 6 illustrate the plan view of realization thirteen (L13) at 290m elevation. Among all the realizations L13 had the minimum amount of ore tonnage and the minimum amount of recovered bitumen; we refer to L13 as the worst case. Figure 7 shows the plan view of realization twenty nine (L29) at 290m elevation. Among all the realizations L29 had the

maximum amount of ore and the maximum amount of recovered bitumen; we refer to L29 as the best case.

5. Check simulation results against the input data and compare results against the kriged models. We checked the quality of geo-model by histogram and variogram reproduction. Figure 8 shows the values at normal scores and the original units. Black lines are cumulative distribution of each realization and the red line is the reference distribution. Figure 9 shows the variogram reproduction at horizontal major and minor and vertical directions. SGSIM has reproduced both histogram and variogram.

Optimal final pit outline design

The final pit limit design was carried out based on the industry standard Lerchs and Grossmann algorithm (Lerchs and Grossmann, 1965) using the Whittle strategic mine planning software (Gemcom Software International, 1998-2008). The kriged, E-type, and fifty SGS realization were imported into the Whittle software.

The ultimate pit limit design was carried out based on the Syncrude's costs in CAN$/bbl of sweet blend for the third quarter of 2008 (Jaremko, 2009). Price of oil was considered US $45 with an exchange rate of 1.25:1 equal to CAN $56.25/bbl SSB for the same time period. We assumed that every two tonnes of oil sands with an average grade of 10% mass will produce one bbl of sweet blend, which is approximately 200 kg. We also assumed a density of 2.1 tonne/m^3 for oil sands, and a density of 1.2 to 1.5 tonne/m^3 for waste material, including clay and sand. Table 1 summarizes the costs used for pit limit design. The mining costs of $12.18 is per tonne of oil sands ore, we assumed a stripping ratio of 1.8:1 for our model this would lead to a cost of $4.6/tonne of material removed (ore and waste).

Table 1. Summary of costs used in pit limit design.

Description	Value	Description	Value
Mining Costs (CAN $/ bbl SSB)	24.35	Mining Costs (CAN $/tonne)	12.18
Upgrading Costs (CAN $/ bbl SSB)	10.05	Upgrading Costs (CAN $/tonne)	5.025
Others (CAN $/bbl SSB)	1.5	Others (CAN $/tonne) 0.75	0.75
Total Costs (CAN $/ bbl SSB)	35.9	Total Costs (CAN $/ tonne)	17.28

Table 2. Final pit and mine planning parameters.

Description	Value	Description	Value
Cutoff grade (%mass bitumen)	6	Processing limit (M tonne/year)	30
Mining recovery fraction	0.88	Mining limit (M tonne/year)	70
Mining dilution factor	1	Stockpile limit (M tonne)	70
Processing recovery factor	0.95	Overall slope (degrees)	20
Minimum mining width (m)	150	Pre-stripping (years)	4

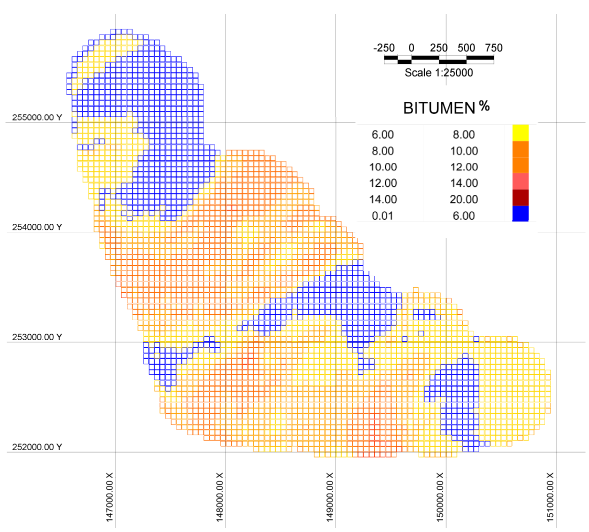


Figure 4. Plan view of the kriged model at 290m elevation.

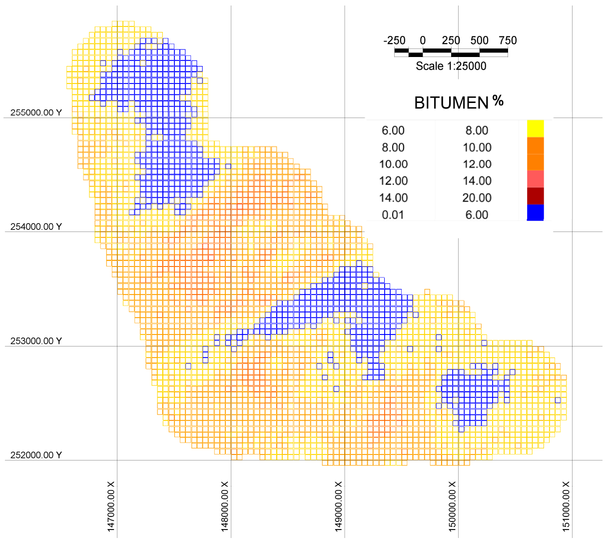


Figure 5. Plan view of the E-type model at 290m elevation.

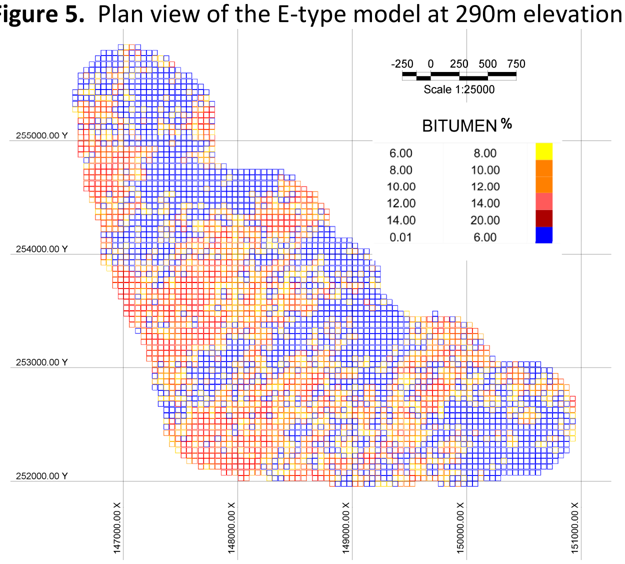


Figure 6. Plan view of the worst case realization (R13) at 290m elevation.

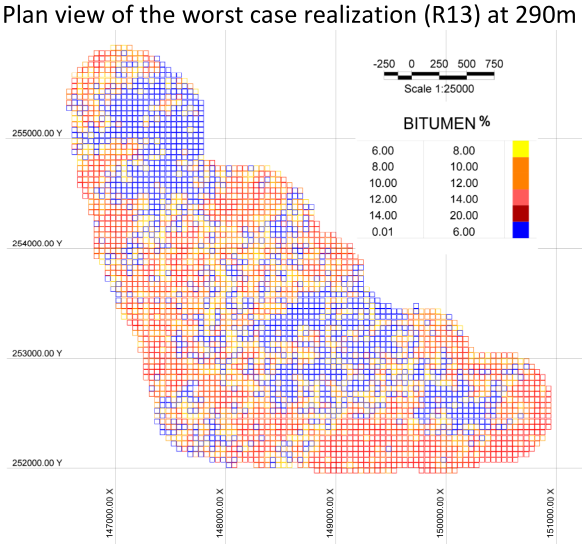


Figure 7. Plan view of the best case realization (R29) at 290m elevation.

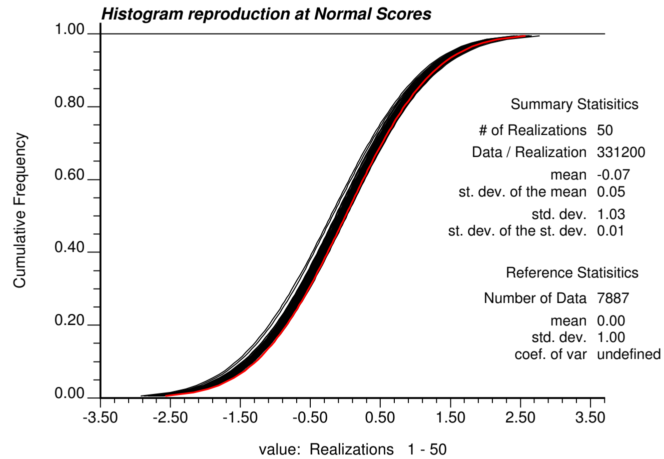


Figure 8a. Histogram reproduction of simulation realizations (black lines) and reference distribution (red line) at normal scores.

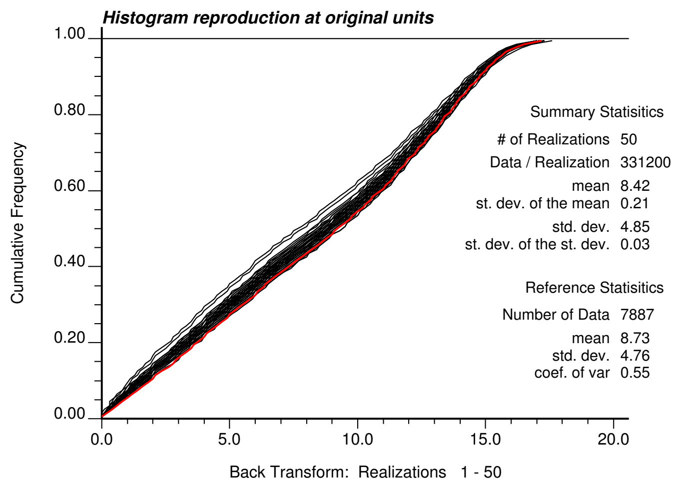


Figure 8b. Histogram reproduction of simulation realizations (black lines) and reference distribution (red line) at original units.

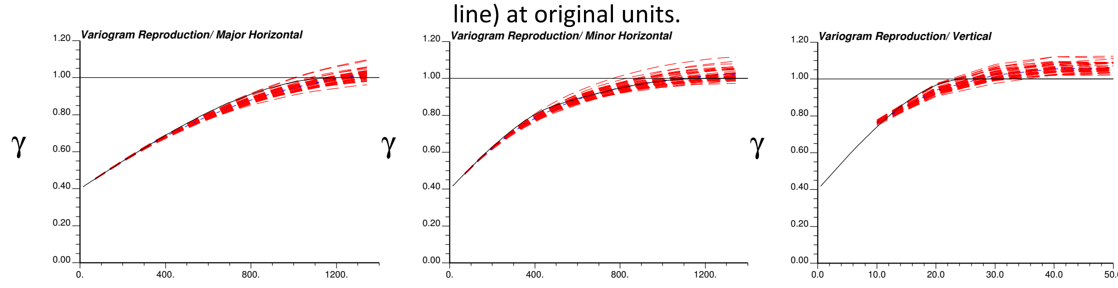


Figure 9. Variogram reproduction of simulation realizations (red dash lines) and reference variogram model (black line).

Table 2 shows the pit design factors used in the study. Thirty nine pitshells were generated using 49 fixed revenue factors ranging between 0.3 to 2.5. The number of pitshells was reduced to 7 after applying the minimum mining width of 150 meters for the final pit and the intermediate pits. Table 3 summarizes the amount of material in the final pit limit for the kriged block model with a 6% cutoff grade. The minimum slope error, the average lope error and the maximum slope error respectively are: 0.0 degrees, 0.2 degrees, 0.4 degrees. The final pit limits was designed for E-type model and all the fifty simulation realizations with the exact same input variables.

Table 3. Materials in the final pit.

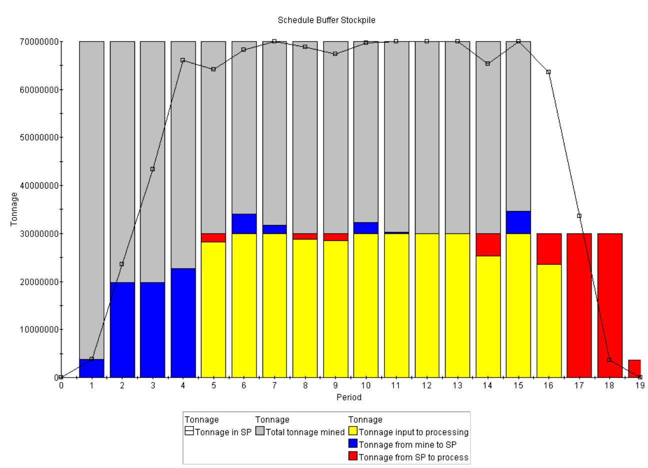
Description	Value
Total tonnage of material (M tonne)	1077.44
Tonnage of ore (M tonne)	423.62
Tonnage of material below cutoff (M tonne)	137.06
Tonnage of waste (M tonne)	516.76
Bitumen recovered (M tonne)	40.30
Stripping ratio (waste:ore)	1.54

Production Scheduling

The kriged model was the basis for production scheduling, we aimed at keeping a uniform processing feed through out the mine life, to achieve this goal we defined four pushbacks based on pitshells number 1, 2, 4, and 7. A fixed lead of three benches was defined, where the lead is the number of benches by which the mining of a specified pushback is ahead of the next one. Four years of pre-stripping was considered to make sure enough space and ore would be available throughout the mine life. Since we wanted to study the effect of geological uncertainty on the production schedule, a buffer stockpile with the capacity of 70 million tonne was included to minimize the effect of geological uncertainty on achieving the production target of 30 million tonnes of ore per year. Although, stockpiles are not used in real oil sands mining operations.

Figure 10a illustrates the kriged block model schedule, in the first four years ore is extracted but the processing plant is not available until year four, the extracted ore in the first four years is sent to the stockpile with the maximum capacity of 70 million tonnes. The total amount of ore within the final pit limit is 424 and 430 million tonnes with an average grade of 10% and 9.3% for the kriged model and the E-type model respectively. Figure 10b shows the schedule for the E-type model, the exact same settings and strategy of the kriged model is followed in this case as well. In both case of the kriged and the E-type models the mine-life is sixteen years but an extra two and half years is used to process the material from the stockpile.

Figure 11a shows the production schedule for realization L13, referred to as the worst case scenario with 341 million tonnes of ore in the final pit and with an average grade of 11%. L13 had the minimum average grade and stripping ratio (1.67:1). The production target in years 5 to 9 are not satisfied with L13 and the mine-life is shorter compared to the kriged model. Figure 11b illustrates the production schedule for realization L29, referred to as the best case scenario with 400 million tonnes of ore reserve with the highest average grade of 11.87% among all the simulation realizations. L29 stripping ratio of 2:1 was the highest among all realizations. Figure 12a and 12b illustrate the yearly production schedule for the pits with minimum and maximum amount of material within the pit limits. Table 4 summarizes the material movement for the kriged, E-type, and simulation results.



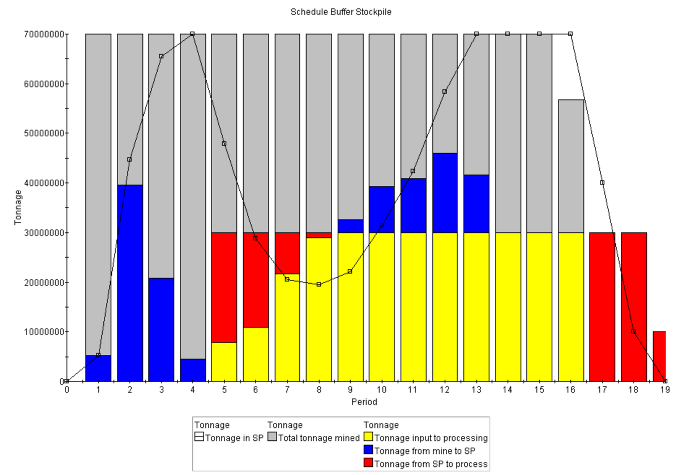
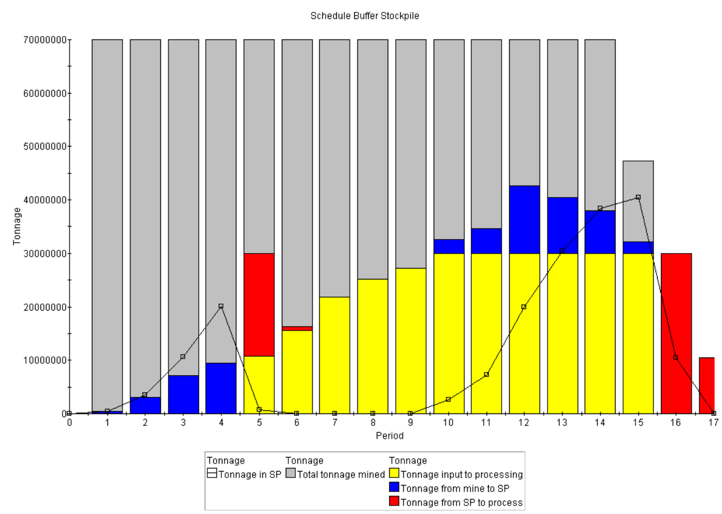


Figure 10. Schedules of Kriged values (a-top) and E-type values (b-bottom).



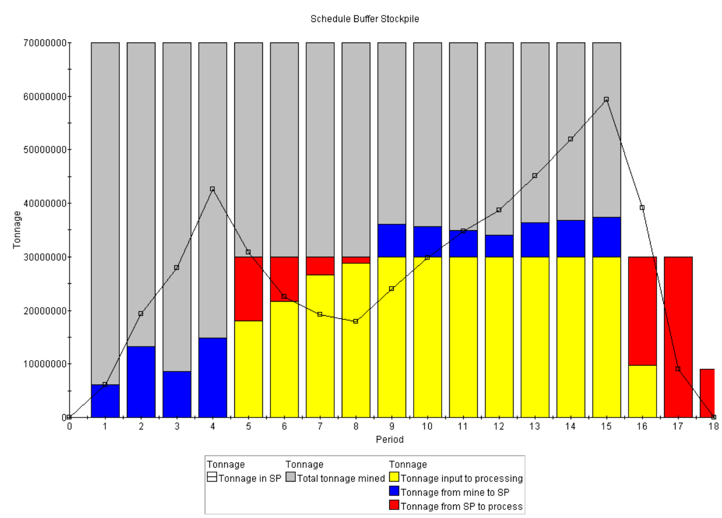
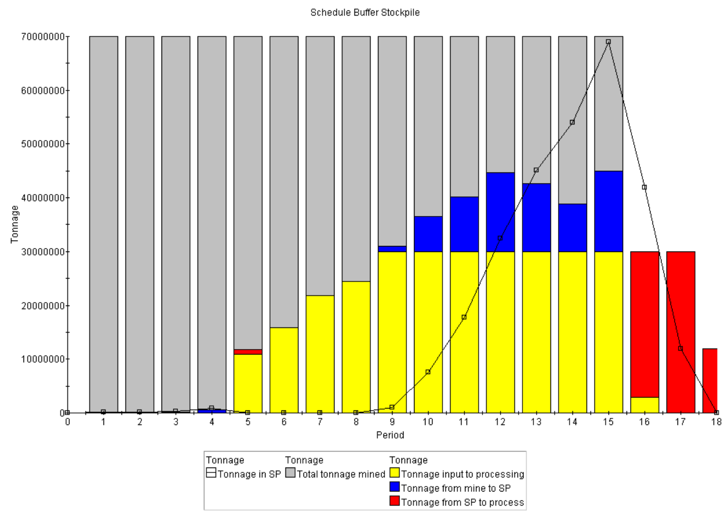


Figure 11. Schedules of Minimum Ore realization 13 (a-top) and maximum ore realization 29 (b-bottom).



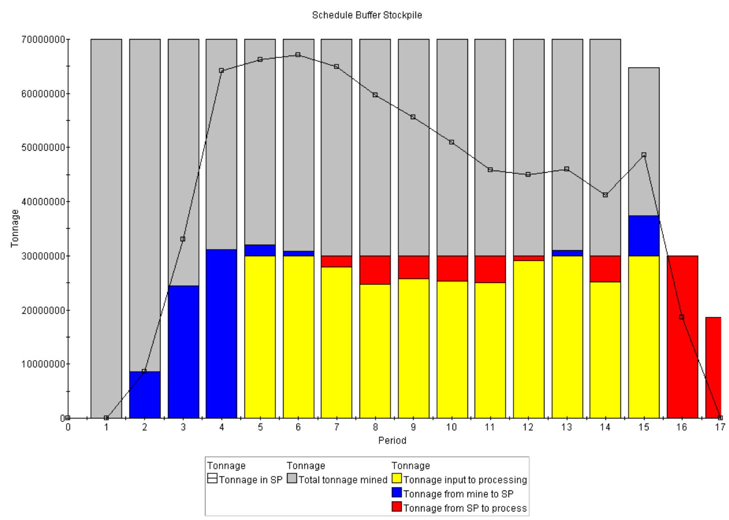


Figure 12. Schedules of minimum (a-top) maximum (b-bottom) NPV, realizations 8 and 19 respectively.

Table 4. Summary of material movement and performance measures for the kriged, E-type and simulation realizations.

		Min	Max	Mean	P50	Krig	E-type
Material Movement	Ore (M tonne)	341 (L=13)	400 (L=29)	372	371	424	430
	Waste(reject) (M tonne)	136 (L=29)	181 (L=30)	160	161	137	148
	Waste(other) (M tonne)	493 (L=31)	532 (L=43)	514	515	517	529
	Total Tonnage (M tonne)	1,002 (L=31)	1,077 (L=43)	1,046	1,047	1,078	1,107
Stripping ratio		1.67 (L=29)	2.01 (L=13)	1.81	1.815	1.54	1.57
Product Bitumen	Input (M tonne)	37.83 (L=13)	46.66 (L=29)	42.59	42.39	42.43	40.05
	Recovered (M tonne)	35.94 (L=13)	44.33 (L=29)	40.46	40.28	40.31	38.04
	Input grade (%mass)	11.09 (L=13)	11.87 (L=19)	11.44	11.42	10.02	9.31
Measures	NPV (million $)	1,109 (L=8)	2,101 (L=19)	1,792	1,807	1,525	1,202
	Life (year)	15.85 (L=4)	17.79 (L=50)	16.63	16.65	18.12	18.33

Discussion

Conditional simulations enable us to provide a set of production scenarios which capture and asses the uncertainty in the final pit outline, net present value, production targets, and the head grade. The probability of each block being extracted in each planning period and the probability that the block would be treated as ore or waste in the respective period could be calculated. In this section, we present and discuss the histograms that quantify the overall uncertainty on the mine production schedule output parameters by means of conditional simulations of the grades. More precisely, the histograms and box plots for the following production schedule output variables are presented:

1. Tonnage of material within the final pit limits.
2. Overall stripping ratio.
3. Total tonnage of ore.
4. Average grade of ore.
5. Tonnage of bitumen produced.
6. Number of barrels of bitumen produced.
7. Net present value.
8. Mine life.

If we follow the production schedule generated based on the kriged model, ideally every block model generated based on the simulation realizations constitutes a plausible scenario with different outcomes. We now have an image of the uncertainty on the production schedule.

Figure 13a illustrates total tonnage of material within the final pit limits, the krig model (the black line) has 1078 million tonnes which is more than the maximum amount recorded for all the simulation realizations. The inter quartile limits are 1039 and 1077 million tonnes. Although the kriged pit has more material than all the simulation models, its stripping ratio of 1.54 is less than 1.67 the minimum stripping ratio of simulation realizations (Figure 13b).

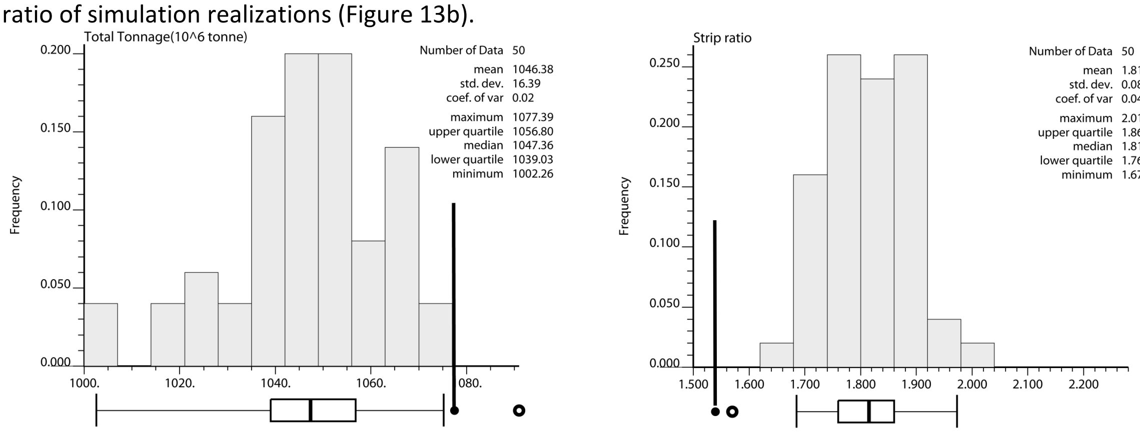


Figure 13. Histograms and box plots of total tonnage of material within the final pits (a-left), and overall stripping ratio (b-right). E-type result by circle and kriged result by black line.

The total tonnage of ore within the kriged model is 424 million tonnes with an average grade of 10% bitumen at a cutoff grade of 6% (Figure 14), where the average total tonnage of ore within the simulation realizations is 372 million tonnes with an average grade of 11.44% (Figure 14 and Table 4). The maximum amount of 400 million tonnes of ore is for realization twenty nine. The lower quartile and upper quartile for the simulation realizations are 361 and 382 million tonnes respectively. The more ore within the kriged and E-type models and assuming the processing plant as the bottleneck of the operation, would result in a longer mine life for the kriged and E-type models. The inter-quartile of the average grade of realizations is between 11.38 and 11.53%, which reflects a very small variance in for the estimated grades by simulation.
Figure 15 illustrates the yearly average head grade for the kriged model (black line), the E-type model (blue dashed line), and the simulation realizations (red dashed lines). As anticipated from the results of Figure 14 the average head grade for the kriged and E-type models are less than the simulation realizations (Figure 15), the head grade variance in the early years of production are higher as it is shown in the box plot in Figure 16, this variance reduces for the later years and almost a uniform head grade could be expected for years 11 to 15.

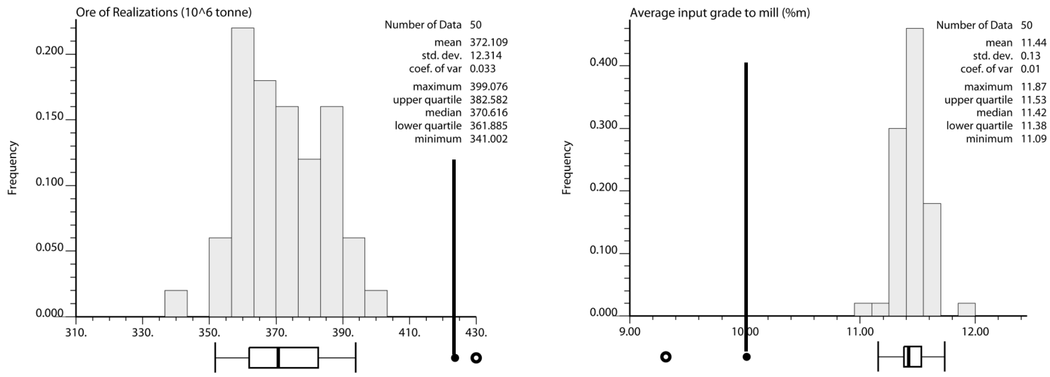


Figure 14. Histograms and box plots of total tonnage of ore (left), and the average head grade in bitumen %mass (right). E-type result by circle and kriged result by black line.

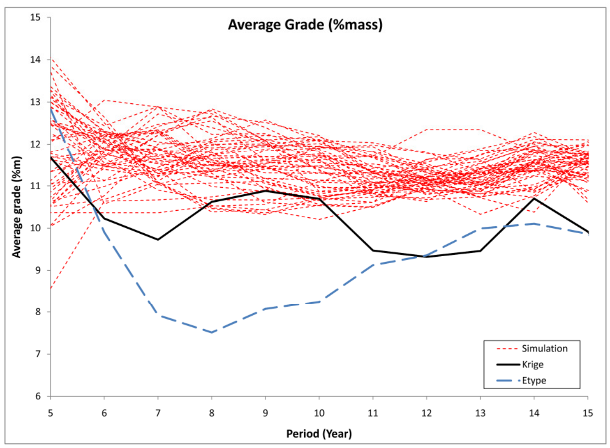


Figure 15. Average head grade simulation realizations, kriging, and E-type models.

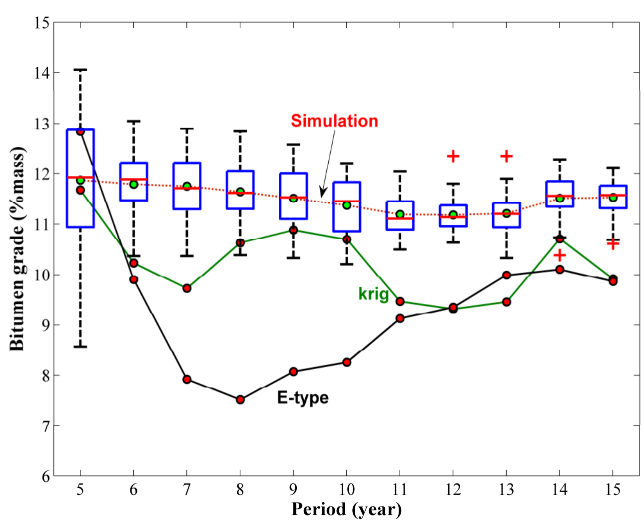


Figure 16. Box plot of simulation head grades (%mass), head grade for kriging, E-type and average simulation models.

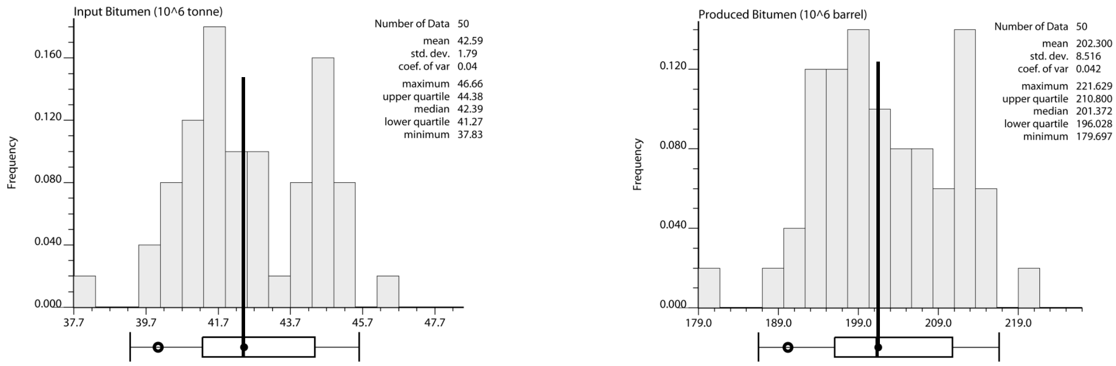


Figure 17. Histograms and box plots of tonnage of bitumen produced (a-left), number of barrels of sweet blend produced in million bbls (b-right). E-type result (circle), kriged result (black line).

Figure 17 illustrates the histograms and box plots for the bitumen as the final product in terms of million tonnes of bitumen and number of barrels of sweet blend produced. The very interesting aspect of these histograms is that the median of the total tonnage of bitumen produced for all the realizations is 42.39 million tonnes, which is almost equal to the tonnage of bitumen produced by the kriged model 42.42 million tonnes.

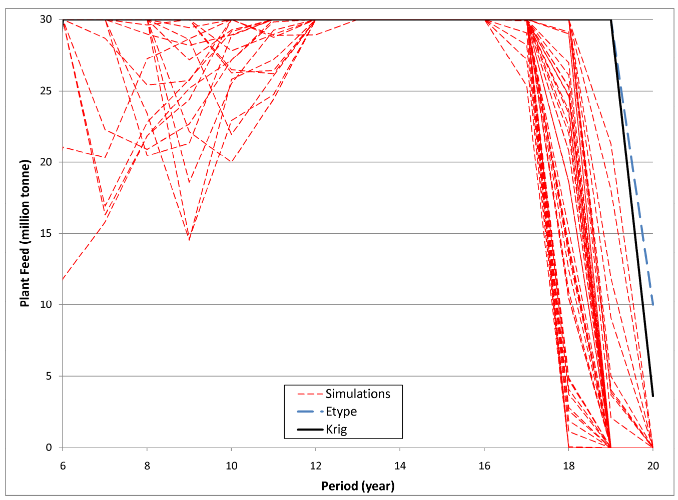


Figure 18. Plant feed (realizations red dash line), kriged values (black line) and E-type (blue dash line).

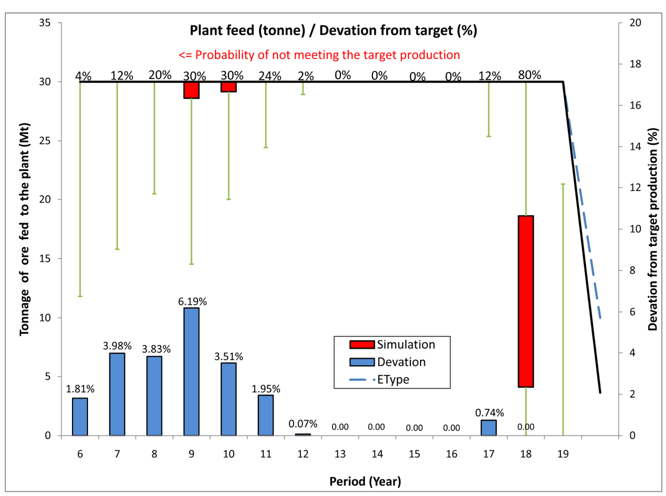


Figure 19. Box plot of the simulation plant feed (red box and green lines), kriged values (black line) and E-type (blue dash line) and deviation from target production.

Comparing the statistics from Figure 14 and Figure 17 reveals that the tonnage of bitumen produced by 424 million tonnes of ore with an average grade of 10% for the kriged model is equal to the median of all the realizations with a lower quartile 361 Mt and upper quartile of 382 Mt of ore with an average grade of 11.44%.

Figure 18 illustrates the plant feed through the mine life for the kriged, E-type, and all the realizations. The higher ore tonnage with lower average grade in the kriged and E-type models has resulted in almost two years longer mine life comparing to the simulation results (Figure 20b). A very important feature of the graph represented in Figure 18 is the target production not met in years 6 to 12 by some simulation realizations. One should take into account that the shortfall in production has happened although we have used four years of pre-stripping and a buffer stockpile. The effect of the grade uncertainty on the production targets would be more severe if the stockpile and pre-stripping strategy was not adopted. Figure 19 illustrates the box plot for the plant feed, the percentage deviation from the target production, and the probability that we would not meet the target production. Between years 8 to 11 the worst case happens where there is a chance of 20% to 30% that we would not meet the production targets. The maximum deviation from the 30 million tonnes target is at year 9 with 6.19% average deviation. Figure 19 clearly illustrates that what are the negative impacts of a deterministic approach to mine planning based on an estimated block model.

Figure 20a shows the histogram and box plot for the NPV, the kriged model NPV is not within the inter-quartile of the simulated models; this is because of the longer mine life and lower average grade for the kriged model. The comparison of the NPV of the kriged model and the simulation results under these circumstances is not a proper economic measure.

Figure 21 shows the cumulative net present value for the kriged, E-type, and simulation results. The longer mine life for the kriged and E-type results led to a flatter slope of the NPV cumulative curves, which has resulted in a smaller NPV compared to the simulation results. Figure 20a and Figure 21 should be analyzed together the median of for the simulation results is 1.8 billion dollars whereas the E-type has an NPV of 1.2 billion dollars compared to 1.5 billion for the kriged model.

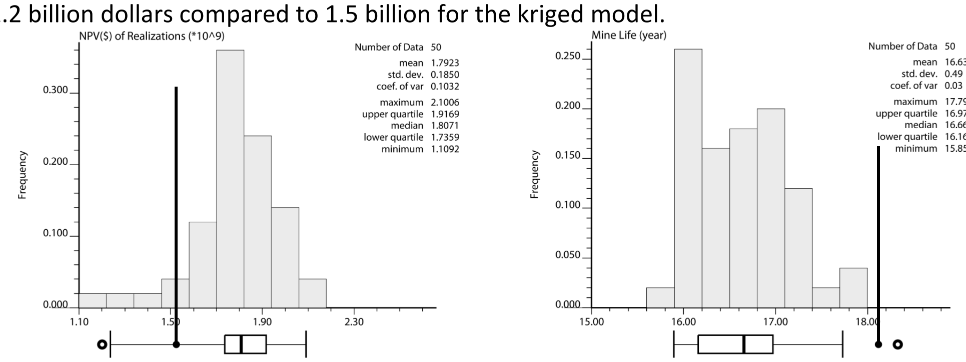


Figure 20. Histograms and box plots of NPV in billion dollars (a-left), and the mine life in years (b-right). E-type result by circle and kriged result by black line.

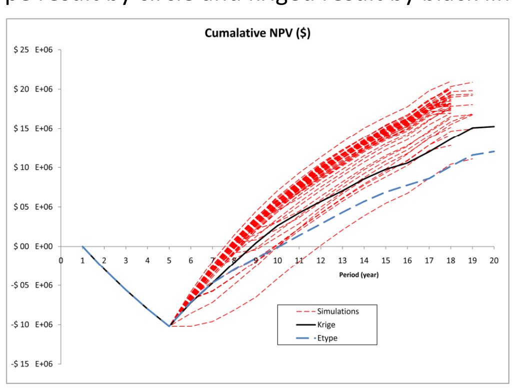


Figure 21. Cumulative discounted cash flow all over the periods for 50 realizations (red lines) and kriging values (black line), a close view at bottom.

Conclusion

A method is presented to transfer geological uncertainty into mine planning. First, Sequential Gaussian Simulation is used to generate fifty realizations of an oil sands deposit. An optimum final pit limits design is carried out for each SGS realization while fixing all other technical and economic input parameters. Afterwards, the long-term schedule of each final pit shell is generated. Uncertainty in the final pit outline, net present value, production targets, and the head grade are assessed and presented. The results show that there is significant uncertainty in the long-term production schedules. In addition, the long-term schedule based on one particular simulated ore body model is not optimal for other simulated geological models. The mine planning procedure is not a linear process and the mine plan generated based on the Kriging estimate is not the expected result from all of the simulated realizations.

In this case study, simulation has been done in data scale at center of each block, and simulated value has been assigned to the block. The differences between simulation results and kriged or Etype results are maybe related to this fact that it is not realistic to assign a data scale simulated value for such a big mass of block. The more applicable and realistic method is to simulate number of point at data scale inside a block and using upscaleing or reblocking method to average out simulated values at inside the block and assign the block. This causes some smoothness in block values which is more reasonable, because it is not very expectable to have same variety as data scale at block scale.

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