Block size selection and its impact on open-pit design and mine planning

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Synopsis

This work evaluates and characterizes the impact of the support size and mining dilution of a block model in the operation and selection of equipment at an open pit mine. An exploratory analysis and geostatistical modelling of the grades assayed on a set of drill hole samples is performed, which allows constructing a grade model on a dense grid by means of a conditional simulation. The grades are then averaged to greater selective mining unit supports in order to proceed with the study and methodology.

First, the metal-tonnage curves are used to analyse the loss of selectivity on the *in situ* resources caused by a change of support. Concerning the ore reserves and their mining sequence, defined in the pit optimization and analysis process, the same curves prove that the loss of selectivity is more accentuated. Second, the importance of the block boundary dilution produced during mining operations is assessed. Its value depends on the amount of ore in contact with waste, on the loading error of the equipment and on the ore loss/waste dilution criterion assumed by the planner. The dilution percentage and the differences between waste and ore grades become higher when the block size decreases. For these reasons, considering the dilution in the production plans makes mining a small support more constraining. An adequate delimitation of the orebody can improve the mining selectivity, leading to greater income. Finally, a study of the increase in mining cost that provides a zero difference in NPV between the different block size options is carried out, in order to determine the maximum increase in mining costs for which it remains profitable to mine at a smaller block size.

Keywords: Mining selectivity, support effect, block boundary dilution, selective mining unit size, block model.

Introduction

In mining projects, the design and production programmes are developed on the basis of a block model. This model requires defining, assessing and assuring many important parameters used in the feasibility study and that may have relevant consequences over the future results of the project. The selection of such parameters is a complex engineering decision due to their great economic impact on the mining operation, as they will significantly affect the mine design and planning. For example, concerning the block model, there are many decisions involving the grades of the elements of interest, by-products and impurities, the dilution percentage, the selectivity and the rock density.

A fundamental parameter of this model is the choice of the block dimensions, since this will condition mining dilution and selectivity, affecting the operation and mining costs. The objective of this study is to quantify the influence of the block size on the mining selectivity and its impact over the projects final economic results (income, costs, and discounted cash flows), a topic that has not been systematically studied in the literature so far.

Definition and sources of mining selectivity

Mining selectivity is understood as the process of separating ore from waste. This concept is strongly related to four effects that imply a degradation of the operational results. These are:

- *Support effect*—the design and planning of the operation is developed on the basis of block models. The block support is more voluminous than that of the assayed samples (drill hole cores). Now, the statistical distribution of the grades, in particular its dispersion and selectivity index, depends on the volume on which the grade is defined, which is known in mineral resource/ore reserve evaluation as the 'support effect'.[1,2,3] This support effect has an impact on the amount of material whose grade exceeds a given cut-off (ore).
- *Information effect*—during the operation, grade control is based on the estimated

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grade values of the elements of interest, not on the real (unknown) block grades. This inevitably implies that some high-graded blocks are underestimated and sent to dump, while other low-graded blocks are overestimated and sent to the processing plant. This phenomenon is known as the 'information effect'[2,3] and results in losses of ore with respect to the ideal case where no block misclassification is made in grade control. This effect will not be analysed in this article; the reader is referred to the specialized geostatistical literature for a quantification of it.[4–6]

- *Geometrical constraints*—mine design requires imposing restrictions on the geometry that rules the extraction of the blocks within the deposit, for instance, overall pit slope angle, bench slope angle and berm width in open pit mining.[7] A high-graded block may be abandoned if the costs involved to reach this block are too high, which implies a loss of ore with respect to the ideal case of a free block selection. Geometrical constraints are one of the modifying factors considered in the international codes for mineral inventory to move from *in situ* mineral resources to ore reserves.[8,9]
- *Dilution*—this term refers to the waste that is not segregated from the ore during the operation, that is, the waste material that is mixed with ore and sent to the processing plant, which decreases the mineral grade and increases its tonnage.[10,11] Such dilution mainly depends on the equipment used in the mining operation, the blast hole pattern, the blasting and operational conditions, as well as on the regularity of the ore/waste contact (this last factor refers to the precision in which the operation can 'cut' the contact between ore and waste).

These four effects on the mining selectivity can be described quantitatively by the so-called 'selectivity curves', which have been introduced in geostatistical applications.[2,12–14] Such curves describe the grade distribution (histogram) and allow the calculation of recovery functions (tonnage, metal content, mean grade, revenue) associated with a specific cut-off grade. In the present study, the tonnage vs. cut-off, mean grade vs. cut-off and metal vs. tonnage curves are used. The last represents the metal content (ore tonnage multiplied by its mean grade) as a function of the ore tonnage, and is useful in analysing the support effect as it shows a hierarchy according to the block size. For example, if for the same mined ore tonnage, a block model produces more metal than an alternative, then the former model is more selective than the latter.

Outline of the study

The proposed methodology considers five stages that allow the comparison of plans generated according to the block size assumed by the planner.

Step 1—Real deposit simulation on a dense grid

This stage consists of an exploratory study and variogram analysis of a real data-set (sample assays from exploration drill holes, composited at 2 m, see Figure 1) from a copper deposit, followed by the generation of simulated grades honouring the spatial continuity and distribution of the data. The simulation corresponds to an interpretation of the deposit with soft boundaries (soft grade transitions) between the different rock types; in the following, it will be considered as the 'true' grade model. It has been performed using the sequential Gaussian algorithm[15] over a mesh (minimum block for selection) of 2.5 x 2.5 x 2.0 m along the east, north and vertical directions, respectively.

Step 2—Analysis of the support effect on resources and reserves

The effect of averaging the simulated grades to blocks (representing the selective mining units, or SMU) on the selectivity of the mining plans is then analysed. For this purpose, the following activities are considered:

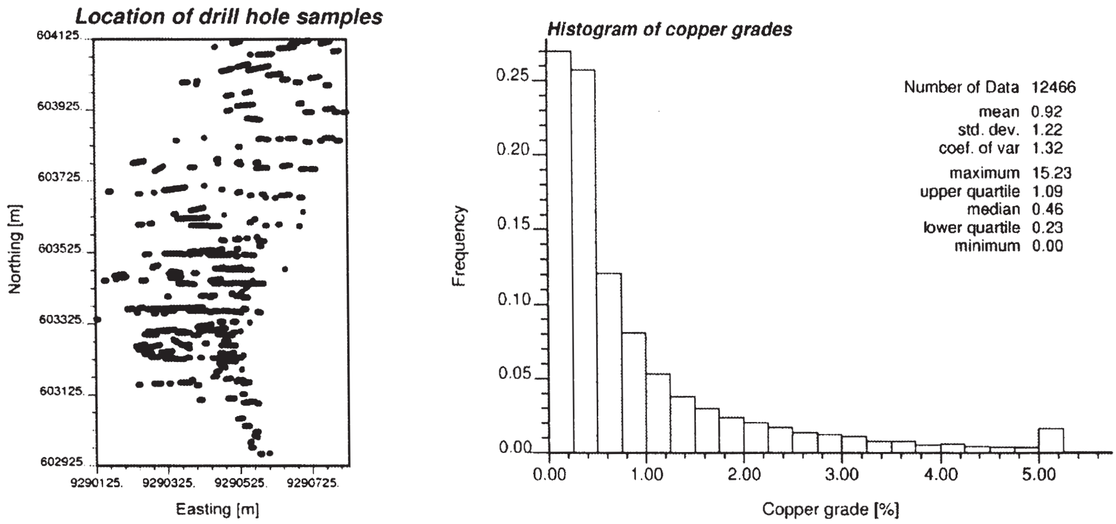

Figure 1—Location map of the available drill hole samples (plan view) and histogram of the assayed copper grades. The last bar of the histogram represents the grades greater than 5.0% Cu

- definition of a set of selective mining unit sizes to be analysed
- regularization (reblocking) of the grades of the simulated dense grid to these SMU
- calculation of the selectivity curves and comparison with the reference case (original simulation over the 2.5 x 2.5 x 2.0 m mesh)
- definition of the ore reserves for a set of technical and economic parameters; generation of a sequence of shells for the optimum pit limit for a given price series
- calculation of the selectivity curves for each case and comparison of the results.

Step 3—Analysis of the economic impact produced by the support effect

To assess the economic impact of the SMU size, the following approach is considered:

- definition of the open pit mining sequence, with phases previous to the definition of roads and accesses (unsmoothed pit)
- calculation of the cut-off grades to use in each case study
- definition of preliminary production plans
- evaluation of the mining plans based on their cash flows.

Step 4—Study of the block boundary dilution

This fourth stage aims at understanding and quantifying the block boundary dilution and at analysing its economic impact. The determination of the percentage of ore in contact with waste gives a good idea of the amount of dilution that may take place during operation. For the analysis, the following activities are developed:

- selection of the ore blocks that belong to the final pit for each case study
- definition of possible loading error of the equipment used in the operation
- calculation of the percentage of dilution in each case
- evaluation of the mine plans based on cash flows, taking into account the expected block boundary dilution.

Step 5—Sensitivity study

The last stage of this work consists of a sensitivity study on several fundamental variables of the mine design and planning, after applying the dilution factor to the mining plans. The goal of the study is to determine the maximum increase in mining costs for which it remains profitable (in terms of NPV) to mine at a smaller block size.

Support effect study

Support effect on the mineral resources

First, an analysis of the mineral resources of the deposit is carried out for three different block size options (Table I). The study of the selectivity curves associated with each block model (in particular, the metal-tonnage curve, see Figure 2) proves that the regularization from a 2.5 x 2.5 x 2 m block model to a 5 x 5 x 4 m block model implies a greater loss of selectivity (loss of metal for a given ore tonnage) than the regularization from 5 x 5 x 4 m to 10 x 10 x 8 m. A variation of the support is therefore more critical in the mining selectivity for small blocks than for big blocks.

Furthermore, when comparing the tonnage vs. cut-off curves at the three supports, one observes only moderate differences for small cut-off values, whereas the curves are considerably altered by the change of support for larger cut-off values. That is, the impact of the block support on the grade distribution is much more important for the high grades than for the low grades.

Support effect on the ore reserves

For each SMU size, an analysis of the ore reserves contained in a series of optimal pit shells for different commodity price scenarios is made. The generation of these optimal shells values each block according to its metal content and production costs and permits selecting the block as ore or waste according to this valuation. Additionally, selectivity curves can be calculated over these optimized pit shells.

The following comments can be made on the effect of the optimization process over the selectivity curves and the comparison between the resource and reserve levels:

- When the block size increases, the ore tonnage increases and the average grade decreases. In this application, when increasing the block size from 5 x 5 x 4 m to 10 x 10 x 8 m, ore tonnage goes up from 118.6

Table I

Selective mining units to be analysed

Block size (m)	Multiplying factor			Objective
	Easting	Northing	Elevation	
2.5 x 2.5 x 2	1	1	1	Reference case
5 x 5 x 4	2	2	2	Estimating the impact of block size along three directions
10 x 10 x 8	4	4	4	Estimating the impact of block size along three directions

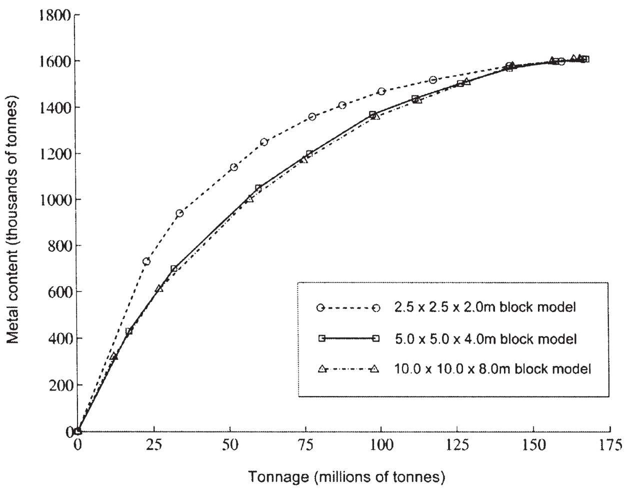

Figure 2—Selectivity curves (metal vs. tonnage) associated with the mineral resources for the different block sizes

to 120.9 million tons, a 2.0% increase, and the mean grade decreases from 1.16 to 1.09 % Cu, a 5.5% loss; accordingly, the metal content falls from 1.372 to 1.322 million tons, which represents a 3.7% loss. This loss in metal content should be accompanied by a significantly lower operation cost in order to improve the overall economic evaluation of the project. Note that the previous results are obtained for the economic envelop of the final pit, prior to scheduling.

- The optimization process accentuates the effect of the support on the mining selectivity, that is, the variations of the metal contents between the three block models are greater than in the case of the *in situ* resources. In other words, the difference in mining selectivity of one block model with respect to another becomes more relevant when defining the economic exploitation limits.
- The discounted cash flow (NPV without accounting for investment) is lower as the block size increases. In this application, it goes down 8.3% when the block size is changed from 5 x 5 x 4 m to 10 x 10 x 8 m.

Analysis of production plans

This section aims at analysing the economic sequence of extraction of some of the nested shells calculated in the previous optimization process, in order to simulate production plans. Since each shell corresponds to a given price, this criterion is equivalent to an ordering by increasing costs (expressed in US$ per pound of produced copper).

The extraction sequence is optimized by taking into account the production and economic parameters, so as to maximize the net present value (NPV), determining which benches in each phase must be mined in each period. The planner can control the extraction of each phase by fixing the following parameters: maximum and minimum bench separation between phases and maximum vertical advance per period. For each production plan, the marginal cut-off grade for the corresponding design price is used, that is, the grade for which the recovered material pays its processing. Table II summarizes the results (produced metal quantities and discounted cash flows) obtained for two cases: SMU size of 5 x 5 x 4 m or of 10 x 10 x 8 m. The following can be stated:

- The differences in metal quantities and cash flows between the two cases increase as time advances, until period 6. After this year, the differences remain more or less constant. This is due to the fact that the highest grades are mined out first and, as mentioned before, the support effect more strongly affects the high grades.
- As stated in the previous section, the metal quantity at each period is greater in the 5 x 5 x 4 m block model than in the 10 x 10 x 8 m block model, a situation that generates a greater NPV in the first case.

Study of block boundary dilution

The percentage of ore material in contact with waste gives a good idea of the possible dilution occurring in the mining operation, depending on the precision with which such a contact is 'cut' by the equipment. To assess this dilution, a simple exercise is proposed, for which it is necessary to know the total area of the ore blocks in contact with waste blocks within the final pit, and the grade distribution of the waste blocks adjacent to the ore. This calculation is carried out for the final pits for each SMU size, by considering the edges of the waste for each one of the block models in the east-west and north-south directions.

The length of the ore-waste contact is calculated by counting the number of waste blocks that are adjacent to an ore block and by multiplying this number by the size of the block. Some reasonable assumptions are required to determine the volume and tonnage of ore loss and/or waste dilution produced by the operation.

- *Error in the ore-waste contact*—it is the error produced in the operation stage when defining and loading the material that must be sent to the processing plant. It can be expressed as the distance of material lost or diluted from the ore-waste contact. Three scenarios are considered where 1, 2, and 3 metre errors are considered. The adequate error length should be defined jointly between the equipment operators and mine planning personnel.
- *Dilution/ore loss criteria*—it defines whether the contact error will be waste dilution or lost ore. Three possible criteria are:

Table II

Comparison of plans of production (in terms of metal content and NPV) associated with two block size options (5 x 5 x 4 m and 10 x 10 x 8 m)

Period	SMU size: 5.0 x 5.0 x 4.0 m				SMU size: 10.0 x 10.0 x 8.0 m			
	Metal [kton]		NPV [kUS$]		Metal [kton]		NPV [kUS$]	
	Incremental	Cumulated	Incremental	Cumulated	Incremental	Cumulated	Incremental	Cumulated
1	68	68	39 810	39 810	59	59	30 851	30 851
2	177	245	108 414	148 224	168	227	102 489	133 340
3	165	410	76 964	225 188	167	395	84 340	217 680
4	144	554	48 567	273 755	131	526	37 324	255 004
5	148	702	36 716	310 471	137	663	30 578	285 582
6	139	840	33 009	343 480	135	798	29 200	314 782
7	143	983	38 164	381 644	134	932	32 633	347 415
8	125	1 108	33 849	415 493	130	1 062	33 868	381 283
9	51	1 159	16 678	432 171	63	1 125	19 612	400 895
Total	1 159	1 159	432 171	432 171	1 125	1 125	400 895	400 895

– *Criterion no. 1* (100% loss)—the objective of the operation is to minimize waste dilution, so that ore is lost so as to clean all possible dilution. The error in the contact is always a loss of ore.
– *Criterion no. 2* (100% dilution)—this is the opposite case of criterion no.1. One wants to recover all the ore, so that all the contact error is included as waste dilution.
– *Criterion no. 3* (50% dilution—50% loss)—is a more realistic criterion and assumes that the errors are equal and compensate in such a way that all the ore loss is replaced by waste dilution.

For each case under study, one obtains correcting factors on the tonnages and the mean grades, which indicate the expected dilution that will occur during the loading operation. As it can be seen, there is a wide range of possible results when combining the criteria of dilution/ore loss and the error in the ore-waste contact (loading error). As an example of the matrix of results, Tables III and IV present a summary of the analysis considering loading errors of one metre and a 50% loss–50% dilution criterion. Note that the expected loading error is the same for all the SMU sizes analysed in this study in order to standardize the calculations and results. This criterion is not necessarily the most realistic for all the cases, as in general the loading error is closely linked to the selectivity of the operation and to the equipment used.

Tables III and IV call for the following comments:

➤ The results vary according to the size of the selective mining unit assumed by the mine planner. On the one hand, the percentage of ore in contact with waste (hence, the percentage of dilution) is smaller when increasing the SMU size, because the ore-waste contact becomes smoother and spatially more regular. On the other hand, the differences between the grades of waste and ore are amplified when the block size decreases. This is explained by the support effect, which implies a greater variability of the grades at small block supports.

➤ When increasing the cut-off grade that defines ore and waste, the percentage of ore that can be diluted by the effect of the ore-waste contact increases.

➤ A suitable operation in the orebody limits can decrease the block boundary dilution to values less than the ones expected by the proposed methodology.

Analysis of the economic impact of block boundary dilution

In this section, an analysis of the economic impact of the block size in the extraction of the ore reserves within the optimal pit shells is carried out. To establish the real differences between the different supports analysed, the previously calculated dilution factors are applied to the preliminary production plans, providing new economic results in each exercise and new comparisons incorporating the economic parameters.

The criterion of waste dilution/ore loss and the loading error to apply on the preliminary plans may naturally differ from place to place and the choice of its magnitude may be left to the mine staff. The following analysis considers assessing dilution factors for the tonnage and grade of a block given a dilution/ore loss criterion and an error in the ore-waste contact (loading error). The loading errors are defined in this case as a percentage of the block size, as it is not the same to consider an error of 1 metre for a block of 2.5 m as for a block of 5 m or 10 m. In Table V, the values of the dilution factors are given for the different block sizes, according to the criterion of dilution/ore loss and the loading error to apply.

Table III

Analysis of block boundary dilution and determination of the dilution factor on grades for a criterion of 50% dilution—50% loss. Blocks with size 5 x 5 x 4 m with a loading error of 1 m

Cut-off (% Cu)	Ore within the pit		Ore-waste contact		50/50 criterion	
	Number of blocks	Ore grade (% Cu)	Length (m)	Waste dilution grade (% Cu)	Diluted Grade (% Cu)	Dilution factor
0.3	410 221	1.13	154 404	0.16	1.11	0.977
0.6	295 890	1.40	222 621	0.38	1.32	0.945
1.0	185 086	1.76	209 442	0.66	1.64	0.929
2.0	51 991	2.67	102 987	1.38	2.42	0.904

Table IV

Analysis of block boundary dilution and determination of the dilution factor on grades for a criterion of 50% dilution—50% loss. Blocks with size 10 x 10 x 8 m with a loading error of 1 m

Cut-off (% Cu)	Ore within the pit		Ore-waste contact		50/50 criterion	
	Number of blocks	Ore grade (% Cu)	Length (m)	Waste dilution grade (% Cu)	Diluted Grade (% Cu)	Dilution factor
0.3	55 701	1.05	22 564	0.14	1.03	0.982
0.6	39 681	1.29	27 011	0.38	1.26	0.976
1.0	23 361	1.64	26 730	0.63	1.58	0.965
2.0	5 127	2.50	9 379	1.49	2.40	0.963

Table V

Dilution factors on grades and tonnages for different levels of loading error and for different dilution criteria

Loading error	Dilution Factors—Block size 10 x 10 x 8 m					
	Criterion 50/50		Criterion 100% dilution		Criterion 100% ore loss	
	Tonnage	Grade	Tonnage	Grade	Tonnage	Grade
10%	0.0%	-1.8%	4.1%	-3.4%	-4.1%	0.0%
20%	0.0%	-3.5%	8.1%	-6.5%	-8.1%	0.0%
30%	0.0%	-5.3%	12.2%	-9.4%	-12.2%	0.0%

Loading error	Dilution Factors—Block size 5 x 5 x 4 m					
	Criterion 50/50		Criterion 100% dilution		Criterion 100% ore loss	
	Tonnage	Grade	Tonnage	Grade	Tonnage	Grade
10%	0.0%	-2.3%	5.3%	-4.3%	-5.3%	0.0%
20%	0.0%	-4.5%	10.5%	-8.2%	-10.5%	0.0%
30%	0.0%	-6.8%	15.8%	-11.7%	-15.8%	0.0%

Loading error	Dilution Factors—Block size 2.5 x 2.5 x 2.0 m					
	Criterion 50/50		Criterion 100% dilution		Criterion 100% ore loss	
	Tonnage	Grade	Tonnage	Grade	Tonnage	Grade
10%	0.0%	-3.4%	7.8%	-6.3%	-7.8%	0.0%
20%	0.0%	-6.8%	15.6%	-11.7%	-15.6%	0.0%
30%	0.0%	-10.2%	23.5%	-16.4%	-23.5%	0.0%

For instance, Table V indicates that for a block size of 10 x 10 x 8 m, when applying a criterion of 50% loss/50% dilution and a loading error of 10% (i.e. 1 m length), a corrective factor of 1.8% must be applied to the grade. The dilution preserves the total material amount; this implies that the dilution affects only the grade, not the tonnage. When applying the dilution factors to the preliminary production plans, one obtains that the metal quantity at each period in the 5 x 5 x 4 m model is greater than the one of the10 x 10 x 8 m model, a situation that generates a greater NPV in the first case. However, the differences of NPV between one support and another decrease from an 8.3% in the preliminary plans to a 6% in the plans with dilution.

Sensitivity study

The objective of this last section is to perform sensitivity analysis on certain fundamental variables related to mine design and planning, before and after applying the dilution factors defined earlier. Special attention is given to the range of mining costs that reproduces the difference of operation costs due to the block size, as the preliminary plans do not incorporate the cost of extraction associated with the block size, that is, the cost associated with the equipment to use in the mine, its productivity and the drill pattern. Thus, we shall determine the increase of mining cost that generates a zero difference in NPV between the different block models.

From the preliminary production plans, one observes a difference between the NPV associated with the sequence of extraction of different block models. For instance, this difference reaches an 8.3% of greater discounted cash flow in the case of the model with a block size of 5 x 5 x 4 m with respect to the model with a block size of 10 x 10 x 8 m. When applying the dilution factors to these preliminary plans, such differences are narrowed and decrease to 6.0%. For both, the preliminary plans and plans with dilution, an exercise is proposed, consisting in determining the percentage of increase of the mining cost that leads to the same NPV for the two block sizes.

The results indicate that the 10 x 10 x 8 m block model leads to an NPV similar to the 5 x 5 x 4 m block model if the mining costs of the former are 14% (preliminary plan) or 10% (plan applying dilution) less than that of the latter. So, the deposit modelled to a block size of 5 x 5 x 4 m can be up to 14% (10%) more expensive to mine than the deposit modelled to a block size of 10 x 10 x 8 m. Over this figure, it is more 'profitable' to mine at a block size of 10 x 10 x 8 m.

Conclusions

The following conclusions and comments can be made from the present study:

- ➤ The support effect generates a loss of selectivity as the block size increases.
- ➤ The greatest impact of the support effect is centred on the high-grade range, for which there is a greater loss of metal content for a given ore tonnage.
- ➤ The loss of selectivity is more important when passing from a model with blocks of 2.5 x 2.5 x 2 m to one of 5 x 5 x 4 m than when passing from the latter to a model of 10 x 10 x 8 m. Put another way, the support effect is more critical for small blocks than for large blocks.

- ➤ The pit optimization process accentuates the effect of the support over the metal contents, that is, the decrease of metal content is greater than at the *in situ* resources level.
- ➤ The preliminary plans do not reflect the cost of extraction associated with the block size (cost associated with the equipment, its productivity and the blast drill pattern). Therefore, a study of the margin of increase in mining cost that provides a zero difference in NPV between the different cases of comparison has been carried out. This study concluded that the deposit modelled to a block size of 5 x 5 x 4 m is economically profitable if its mining cost is less than 14% more expensive than that of the deposit modelled to a block size of 10 x 10 x 8 m.
- ➤ The calculation of block boundary dilution varies in function of the SMU size assumed by the planner. There exists a wide matrix of possible results when combining the criteria of dilution/ore loss and the loading error of the equipment. The criteria to take into account should be decided according to the policy of the company evaluating the project.
- ➤ The percentage of ore in contact with waste is greater when assuming a smaller block size. Therefore the percentage of dilution increases when the block size decreases. Together with the support effect, this dilution effect implies that mining small block models is much more constraining and subject to ore losses than mining large block models.
- ➤ The magnitude of the dilution factors on tonnages and grades differ according to the block size of the analyzed model. A greater factor has to be applied to the smaller block sizes, because the contact perimeter between waste and ore is more important when the block size is small.
- ➤ When considering dilution factors, the mining cost of the deposit modelled at a block size of 5 x 5 x 4 m can be up to 10% more than that of a deposit modelled with a block size of 10 x 10 x 8 m. If an extraction with a mining cost below this 10% can be obtained, it is economically viable to be selective and work at a block size of 5 x 5 x 4 m.
- ➤ It is advisable to analyse the incidence of the block orientation in the calculation of boundary dilution, so as to look for the configuration that better delineates the ore/waste contact and minimizes the dilution factors to apply to the mining plans.

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