

# A Risk Analysis Based Framework for Strategic Mine Planning and Design—Method and Application

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**Abstract** Assessment and management of orebody uncertainty is critical to strategic mine planning. This paper presents an approach that consists of a series of procedures for risk assessment in pit optimisation and design. Multiple block grade simulations are processed in Whittle Software to produce a distribution of possible outcomes in terms of net present value. Examples from an open pit mine are used to illustrate the practical application of the methodology.

## Introduction

Traditionally, determination of the spatial distribution of grades in an orebody model is based on geostatistical estimation. The main drawback of estimation techniques, be they geostatistical or not, is that they are unable to reproduce the in situ spatial variability as inferred from the available data. Ignoring such a consequential source of risk and uncertainty may lead to unrealistic production plans (e.g. Dimitrakopoulos et al. 2002). In dealing with uncertainty on the spatial distribution of attributes of a mineral deposit, several models of the deposit can be generated based on and conditional to the same available data and their statistical characteristics. These models are all constrained to:

- reproduce all available information and their statistics, and
- represent equally probable models of the actual spatial distribution of grades.

The availability of multiple equally probable models of a mine deposit enables mine planners to assess the sensitivity of pit design and long-term production scheduling to geological uncertainty. This approach has been proposed by many authors over the last 20 years (David 1988; Journel 1992; Ravenscroft 1992; Dimitrakopoulos 1998; Godoy 2002; Dimitrakopoulos et al. 2007; Kent et al. 2007;

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and others). Figure 1 illustrates the difference between the traditional process used to convert a mineral resource into an ore reserve and the risk based approach based on the technique of conditional simulation.

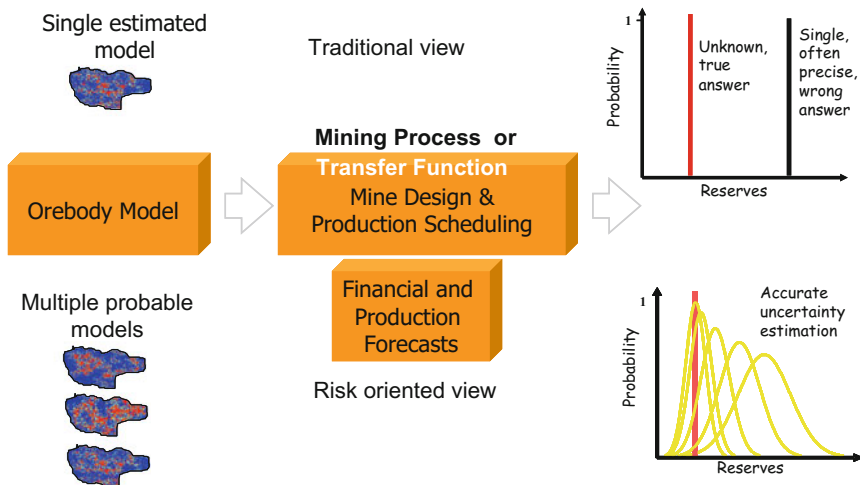
The goal of this paper is to provide mining planning engineers a series of procedures that can be used to consider the effects of grade uncertainty in mine planning studies. Four cases have been selected to illustrate different types of applications:

1. uncertainty analysis of an ultimate pit shell—Net Value (NV), costs, tonnage, grade and metal;
2. identification of areas of upside potential and downside risk;
3. trade-off analysis for cut-back depletion strategies; and
4. assessment of uncertainty related to ore blocks driving the increment between the successive pit shells.

In the following sections, each application is developed separately and includes a step-by-step description of the procedure and a discussion of the results obtained in a real case application.

### Uncertainty Analysis for an Ultimate Pit Shell

The objective of this analysis is to evaluate the sensitivity of key pit optimisation results to grade uncertainty. The process known as pit optimisation is traditionally carried out based on the estimated resource model and using the nested pit



**Fig. 1** Conversion of a mineral resource into an ore reserve, traditional and risk oriented views

implementation of the Lerchs-Grossmann algorithm of the Whittle Software (Lerchs and Grossmann 1965; Whittle 1999). The result of the optimisation process is a series of incremental pit shells. Different criteria can be used to select the ultimate pit shell including net pit value and the net present value based on a referential mining sequence. This ultimate pit shell is then used as the basis for pit design and planning. Using conditionally simulated models as input, Whittle's analysis program (FDAN) may be used allowing the quantitative assessment of risk due to uncertainty on the real, but unknown, distribution of grades. In the procedure proposed below an ultimate pit shell produced in Whittle is evaluated against a series of simulated models of the orebody.

To assess uncertainty on the main parameters driving the selection of the ultimate pit shell the following procedure is proposed:

- From the Whittle result file produced by the pit optimisation process, generate a Whittle pit list file containing information about the smallest numbered pit that each block is part of.
- Apply the pit list file produced in Step 1 to each one of the simulated orebody models.
- Run the analysis program configured to generate the same information, previously generated by analysis on the original pit optimisation. The analysis must be carried out for each one of the available simulated models.

The above procedure generates a range of alternative outcomes for the original optimisation process. This allows the planner to evaluate the likely range of contained ore, metal and a series of key economic indicators. Figure 2 shows the predicted ore tonnage produced by risk analysis. Up until pit 27, the cloud of cumulative tonnages derived from the simulated models present an average decrease of approximately 9.76% in relation to the tonnage predicted by the estimated model. At pit 27 the estimated model indicates approximately 180.3 Mt against an expected value of 164.6 Mt derived from the simulations. The expected outcomes of contained ore go from 163.3 to 166.1 Mt, which corresponds to a range of -0.83 to +0.92% in relation to the expected value derived from the simulations. The same type of analysis carried out on the average mill feed grade (Fig. 3) shows a decreasing overestimation in grades of the estimated model in relation to the simulated models. At pit shell number 1, the estimated model predicts an average mill feed grade of 2.6 g/t, while the simulations indicate an expected grade of 2.2 g/t. At pit 27 the estimated model indicates approximately 1.98 g/t against an expected value of 1.95 g/t derived from the simulations. The risk profile on mill feed grade goes from 1.93 to 1.98 g/t, which corresponds to a range of -1.24% to +1.32% in relation to the expected value. Figure 4 shows the predicted recovered metal produced by the analysis. Up until pit 27, the cloud of cumulative recovered ounces derived from the simulated models present an average decrease of approximately 17.41% in relation to the ounces predicted by the estimated model. This result indicates that the estimated model is potentially overestimating grades as an effect of excessive smoothing. At pit 27 the estimated model indicates 9.84 Moz

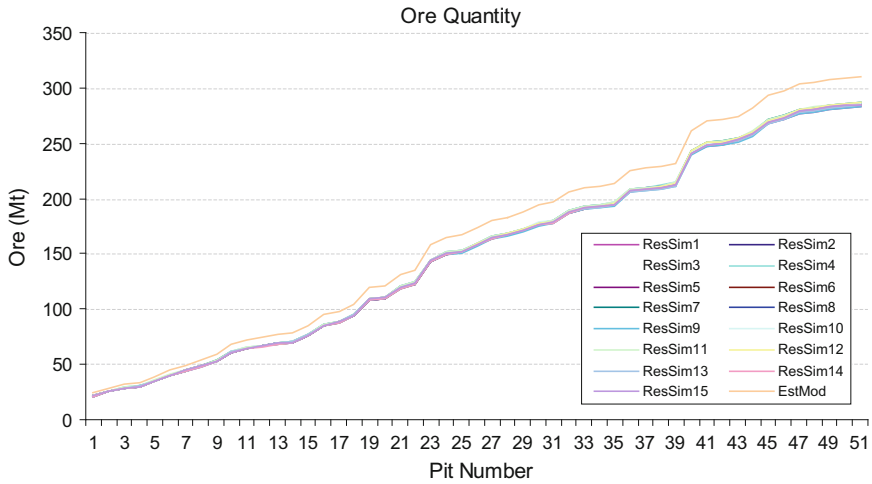


Fig. 2 Uncertainty in ore tonnes for incremental pit shells

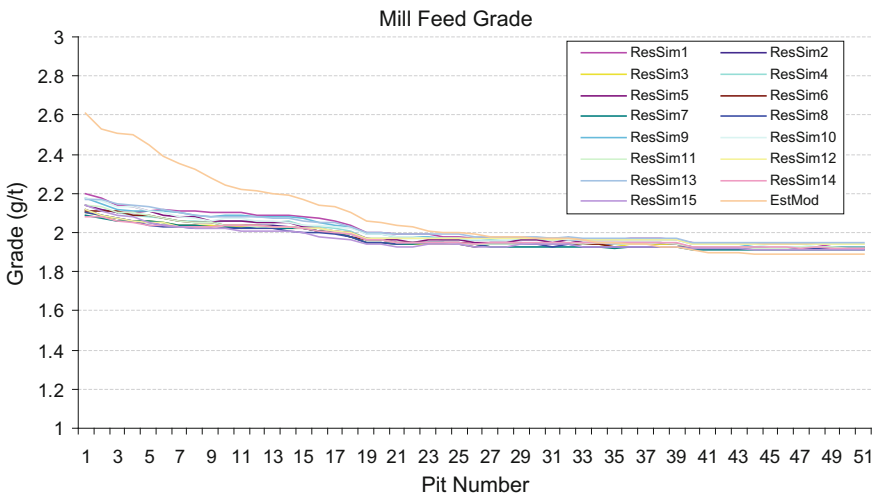
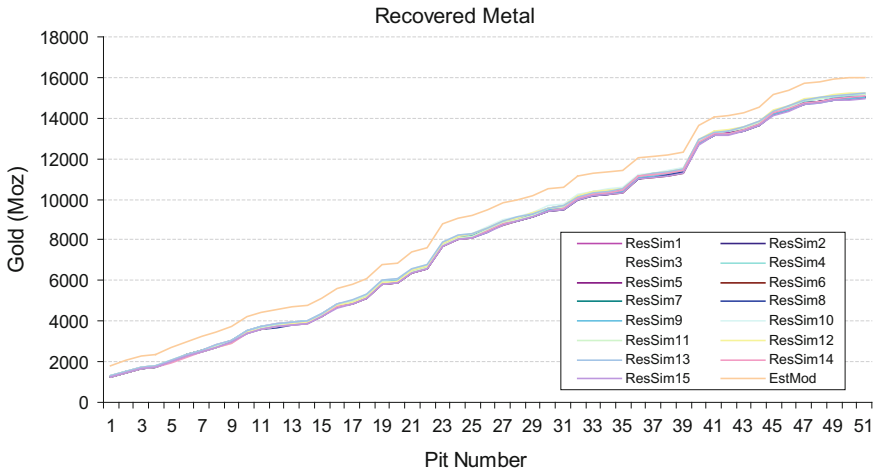


Fig. 3 Uncertainty in mill feed grade for incremental pit shells

against an expected value of 8.85 Moz derived from the simulations. The risk profile on recovered ounces goes from 8.72 to 8.98 Moz, which corresponds to a range of -1.4 to +1.58% in relation to the expected value.

The combination of the overestimation in ore tonnage and mill feed grade has a direct impact on the performance of the pit by pit Net Value. Figure 5 presents the results obtained for the pit Net Value.



**Fig. 4** Uncertainty in recovered ounces for incremental pit shells

It suggests that the estimated model overestimates the pit value over all optimised pit shells. Up until pit 27, the cloud of cumulative Net Value derived from the simulated models present an average decrease of approximately 33.39% in relation to the Net Value predicted by the estimated model. It also indicates a downside potential for pit 27 with expected NV equivalent to \$951.6 M or a 26.12% decrease in relation to the \$1288 M obtained for the analysis on the estimated block model. It is interesting to note that if Net Value was to be used as the criterion for the selection of the ultimate pit shell the simulations would agree with the estimated model by indicating pit 27. The range of expected Net Values goes from \$890 to \$1013 M, which corresponds to  $-6.47\%$  to  $+6.41\%$  in relation to the expected value.

## Identification of Upside and Downside Potential

The goal of this analysis is to explore the possible downside/upside potential of the selected ultimate pit shell regarding the available grade uncertainty models. To achieve this independent pit optimisation runs are carried out on each simulated model. The analysis is divided into two parts:

1. First, each optimisation output is evaluated in terms of contained ore, grade, metal and pit value. This provides a quantification of the project potential given realistic scenarios of the spatial distribution of grades.
2. The second part looks into the spatial extends of a specific pit shell as produced for each independent optimisation. The comparison of this ‘cloud’ of pit shells against a given pit design provides an assessment of areas with upside/downside

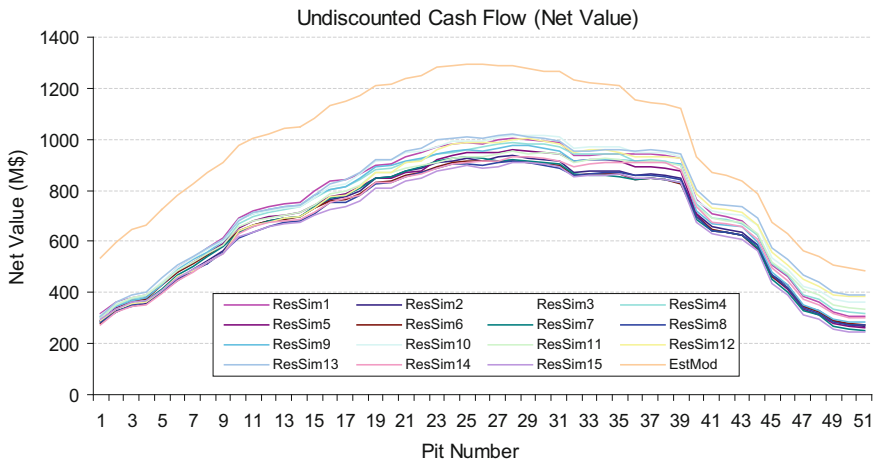


Fig. 5 Uncertainty in Net Value for incremental pit shells

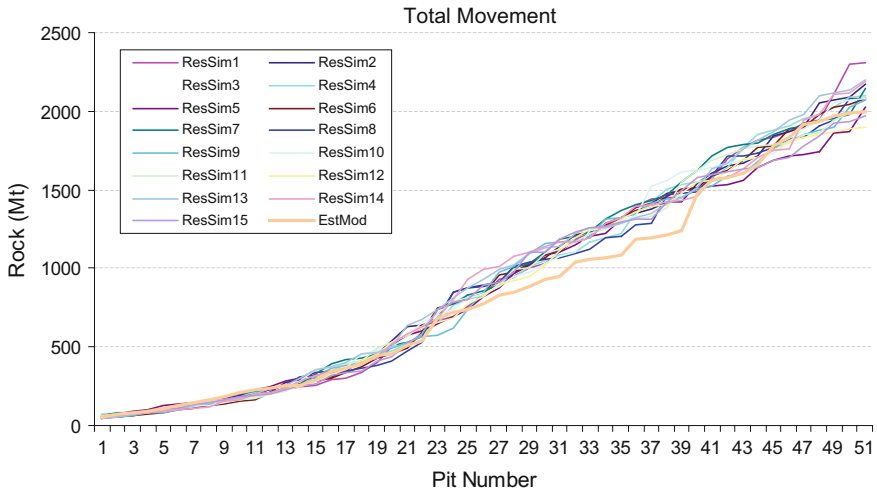
potential and can be used to define targets for additional drilling. It also provides an indication on the robustness of a given pit design in relation to grade uncertainty.

The procedure proposed for the development of this analysis is the following:

- Create a new project in Whittle and import each one of the simulated models. Next, set the optimisation parameters for the optimisation run.
- Apply the same parameters to each model and run the optimisation. The process will generate a series of Whittle result files, one for each simulated model. This step usually requires a large amount of disk space.
- Run analysis program configured to generate the relevant summary information. The analysis must be carried out for each one of the available simulated models.
- Produce cross-sections for a selected pit number over all optimised models.

Contrary to developing a risk analysis on a given ultimate pit shells, as carried out in the previous section, the above procedure generates alternative sets of incremental shells, one set for each simulated model. Figure 6 shows the total rock contained on each incremental shell as produced by each independent optimisation.

The thick orange line corresponds to the results obtained from the analysis on the incremental shells optimised on the estimated model, hereafter termed estimated pit. The thin lines correspond to the results obtained from the analysis on the incremental shells optimised on each one of the simulated models, hereafter termed simulated pits. The figure shows that up to pit shell 24 the estimated and simulated pits present an equivalent quantity of contained rock, that is, they have approximately the same volume. From around pit shell 25, there is a clear separation with the simulated pits showing a progressive increase in comparison to the estimated pit. This scenario remains the same until pit shell 39, when the estimated pit starts to

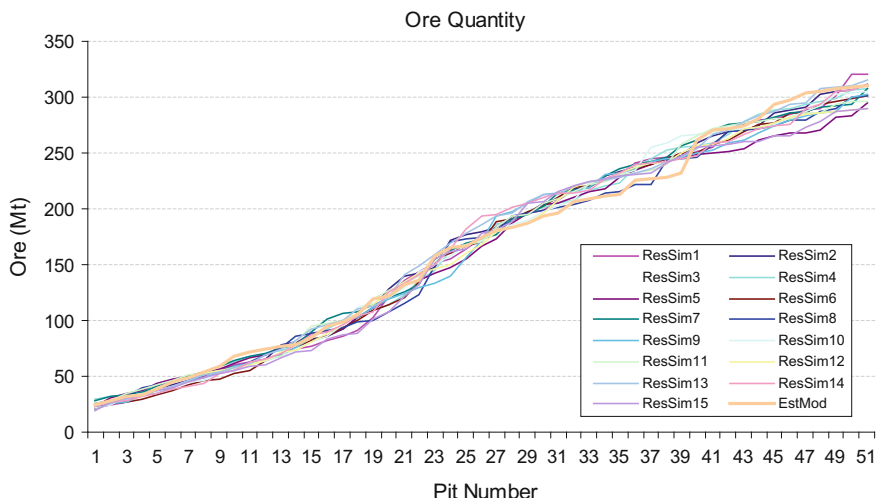


**Fig. 6** Total rock tonnage contained on incremental pit shells. Estimated pit is depicted by the thick orange line and the remaining coloured thin lines correspond to simulated pits

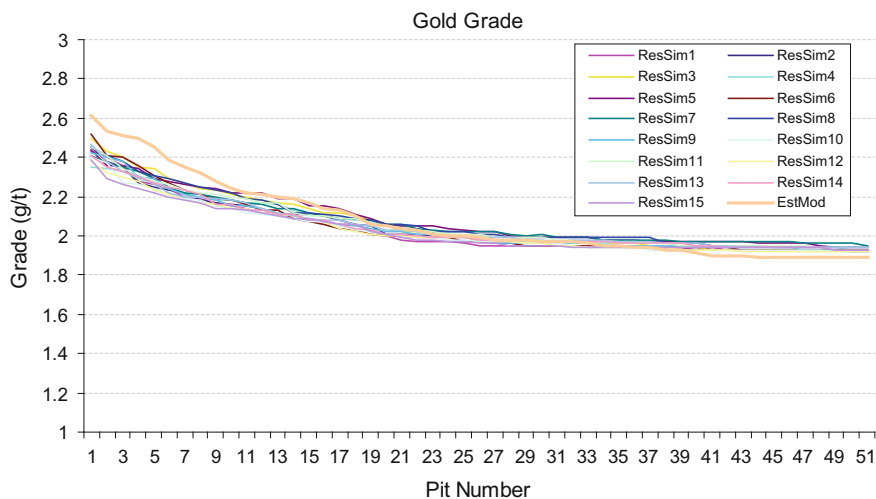
converge to the cloud of simulated pits. Pit shell 27 is of particular interest as it corresponds to the pit selected as a basis for pit design. For pit shell 27, the average contained rock over the simulated pits is 925 Mt against 828 Mt in the estimated pit, which corresponds to an increase of approximately 11.7%. Figure 7 presents the results obtained for the total contained ore. In this case, estimated and simulated pits show similar behaviour as the total rock, only that the magnitude of the differences is smaller. For pit shell 27, the average contained ore over the simulated pits is 183.9 Mt against 180.3 Mt in the estimated pit, which corresponds to an increase of approximately two per cent. The risk profile on the contained ore goes from 174 to 195 Mt, which corresponds to a range of  $-5.92$  to  $+6.06\%$  in relation to the expected value. In terms of mill feed grade, the estimated pit starts with 2.61 g/t against an average 2.43 g/t over the simulated pits. This difference decreases with incremental pit shells and become equivalent at pit shell 27 (Fig. 8).

The risk profile on mill feed grade goes from 1.95 to 2.02 g/t, which corresponds to a range of  $-1.61$  to  $+1.92\%$  in relation to the expected value. Figures 9 and 10 present the results obtained for recovered metal and total pit value.

As expected, the recovered metal for estimated and simulated pits follow the same trends seen on the ore tonnage graphs. For pit shell 27, the recovered gold over simulated pits is 10.03 Moz against 9.84 MOz in the estimated pit, which is an increase of approximately 0.9%. This combination of slightly higher metal with considerable more rock tonnage in the simulated pits translates into a reduced net pit value when compared to the estimated pit. The estimated pit presents a consistently higher Net Value until pit shell 39 when the total rock tonnage becomes equivalent to that shown on the simulated pits. For pit shell 27 the average Net Value over simulated pits is 1159 million dollars against 1288 million in the



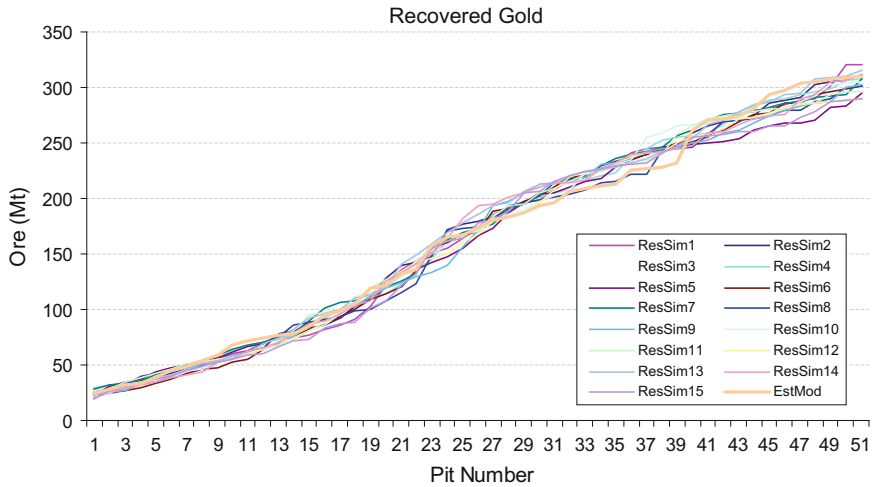
**Fig. 7** Total ore tonnage contained on incremental pit shells. Estimated pit is depicted by the thick orange line and the remaining coloured thin lines correspond to simulated pits



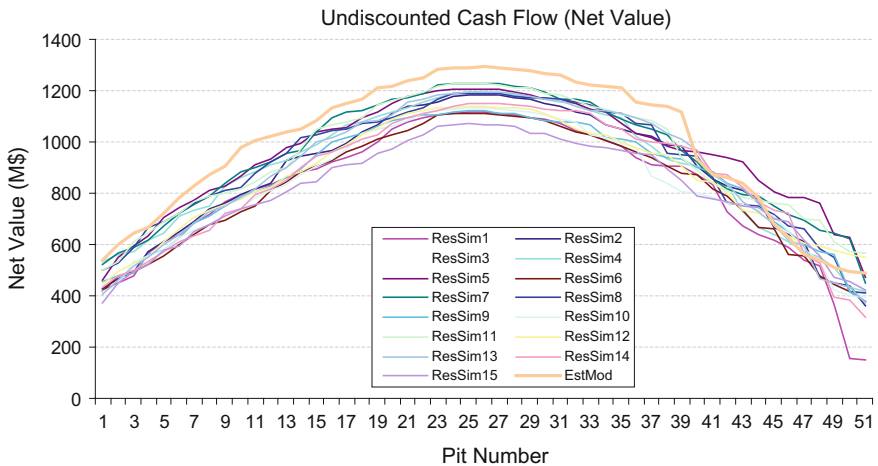
**Fig. 8** Average grade contained on incremental pit shells. Estimated pit is depicted by the thick orange line and the remaining coloured thin lines correspond to simulated pits

estimated pit (approximately 10% less). The risk profile on Net Value goes from \$1068 to \$1292 M, which corresponds to a range of -7.86 to +6% in relation to the expected value. It is interesting to note that as for the estimated model the maximum Net Value over all simulated pit corresponds to pit shell number 26. This shows that pit shell 26 is quite robust with regards to grade uncertainty. Another conclusion





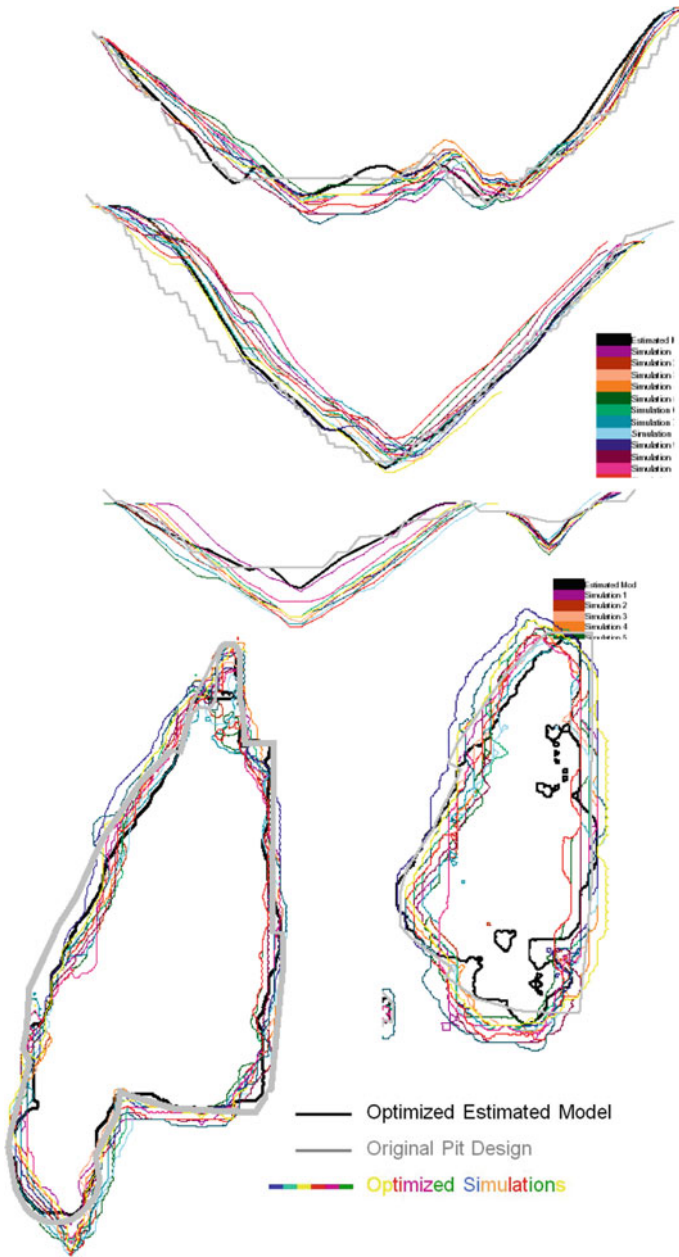
**Fig. 9** Total recovered metal contained on incremental pit shells. Estimated pit is depicted by the thick orange line and the remaining coloured thin lines correspond to simulated pits



**Fig. 10** Total pit value of incremental pit shells. Estimated pit is depicted by the thick orange line and the remaining coloured thin lines correspond to simulated pits

that can be drawn from these results, which is coherent with the results obtained in the analysis presented in the previous section, is that there is a global overestimation of grades and ore tonnage by the estimated model as compared to the simulated models.

A series of cross-sections were produced for pit shell 27 over all optimised models and for a pit design. These cross-sections were overlaid and are presented in Fig. 11. The main conclusions drawn from the analysis of these cross-sections are



**Fig. 11** Cross-sections produced for pit shell 27 over all optimised models overlaid with actual pit design

the following. The simulated pits closely honour the eastern wall of the current pit design, showing that the eastern slope is stable with relation to grade uncertainty. In general, there is a more pronounced fluctuation in the western wall which indicates higher levels of grade uncertainty. The current design has an extension of the western wall, which is not included in the optimisations of both estimated and simulated pits. This extension represents a major downside potential zone and goes from the actual pit surface to the lowest levels of the pit. The simulated pits indicate an upside potential region at the southwest zone of the pit where the simulated pits reach levels that are deeper than the current pit design. The spread of cloud of simulated pits is shown to be low from the surface down to level-350. Below that the spread increases considerably. This reflects the increasing uncertainty on the distribution of grades at depth and is directed related to the lack of drilling.

## Trade-off Analysis

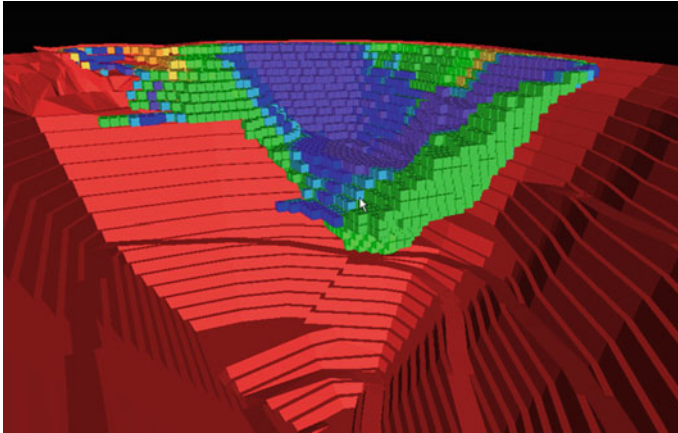
The goal of this analysis is to quantify the impact of grade uncertainty to tonnage, grades, metal and Net Value of two different mining strategies. Scenario 'A' considers the depletion of a cut back as a single stage, while scenario 'B' defines two separate stages. The analysis consists on the quantification of uncertainty on key mining physicals and economic parameters for the two mining scenarios considered. The objective is to evaluate if one of the scenarios is any better in terms of the compromise between Net Value and risk exposure. The procedure proposed to develop the analysis is the following:

1. generate a wireframe describing the cut-back,
2. filter the block model against the wireframe and retain the blocks lying inside the cut-back as new block model,
3. export the block model produced above into a Whittle Model File,
4. repeat steps 2 and 3 for each one of the simulated models,
5. for each model produced in the previous steps calculate the relevant summary information, and
6. repeat steps 1 to 6 for stages 1 and 2 that correspond to another mining scenario.

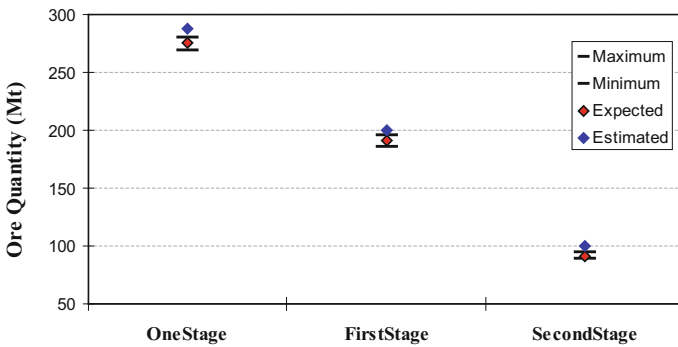
The procedure was carried out for a total of 16 models, corresponding to 15 grade simulations plus the estimated model. Figure 12 presents a 3D view of the cut-back showing its position in relation to the current pit design. Figure 13 shows the results in terms of contained ore for each mining scenario:

- the first profile corresponds to the scenario 'A', which corresponds to the cut-back depletions as a single stage; and
- the other profiles correspond to the first and second stages of scenario 'B'.

The expected combined ore tonnage of scenario 'B' is 2.3% higher than scenario 'A' (28.2 Mt against 27.6 Mt). The risk profile for scenario 'A' shows a range of



**Fig. 12** View of the cut-back against the pit design. The colours indicate different incremental pit shells



**Fig. 13** Risk profiles on contained ore of two mining scenarios

variation that corresponds to 5.2% of the expected ore tonnage. For the two stages of scenario ‘B’, these ranges correspond to 5.19% and 6.51% respectively. For scenario ‘A’, the contained ore predicted by the estimated model is 4.16% higher than the expected tonnage derived from the simulations. For the first and second stages, this difference corresponds to 4.63% and 9.89% respectively. Figure 14 shows the results in terms of recovered gold.

The expected recovered metal of scenario ‘B’ is approximately 1.7% higher than in scenario ‘A’ (1.63 Moz against 1.60 Mt). The risk profile for scenario ‘A’ shows a range of variation that corresponds to 7.1% of the expected tonnage. For scenario ‘B’ this ranges correspond to 8.5% and 12.3%. For scenario ‘A’ the recovered gold predicted by the estimated model is 10.43% higher than the expected tonnage derived from the simulations. For the first and second stages of scenario ‘B’, this

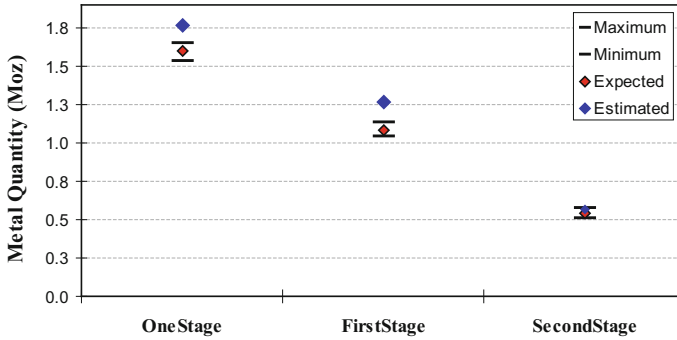


Fig. 14 Risk profiles on recovered metal of two mining scenarios

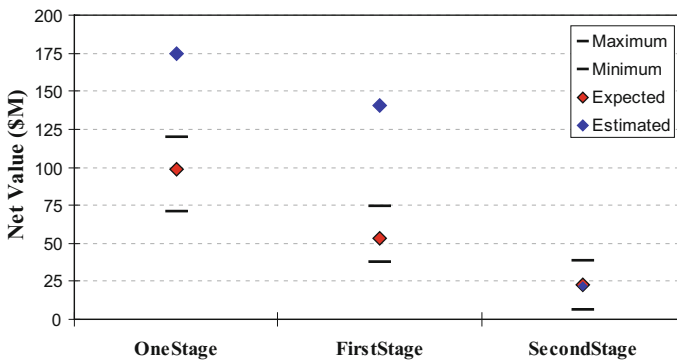


Fig. 15 Risk profiles on pit value of two mining scenarios

difference corresponds to 16.70% and 3.61% respectively. Figure 15 summarises the results in terms of Net Value.

The expected Net Value of scenario ‘B’ is approximately 22.3% lower than in scenario ‘A’ (\$76.5 M against \$98.4 M). The risk profile for scenario ‘A’ shows a range of variation that corresponds to 50% of the expected Net Value. For scenario ‘B’ the ranges correspond to 68.61% and 141.2% for the first and second stages respectively. The combined expected range of variation for scenario ‘B’ corresponds to 67.4%. For scenario ‘A’ the Net Value predicted by the analysis on the estimated model is 76.85% higher than the expected tonnage derived from the simulations. For the first and second stages this difference corresponds to 162.47% and -2.48% respectively. The results obtained in terms of the risk profiles indicate that both scenarios present high risk of not achieving predicted Net Value. In addition, it was clearly identified that the volume related to stage 1 of the scenario ‘B’ is the one with all the risk.

It is important to note that this analysis is rather simplistic in the sense that the time effect of money is not included. Ideally, a mining schedule should be

developed in order to account for the mine sequencing. However, the second scenario roughly accounts for the sequencing by developing the depletion in two stages. The analysis indicated that the risk of missing the target when mining the volume related to the first stage of the second scenario is extremely high. This warrants a detailed review of the estimated grades in this volume.

## Risk Analysis on Ore Blocks Driving a Pit Increment

The aim of this analysis is the quantification of uncertainty on the ore blocks driving the increment between two successive Whittle pit shells. To assess uncertainty on the main parameters driving increment between two successive pit shells, the follow procedure is proposed:

1. From the Whittle result file produced by the pit optimisation process generate a Whittle pit list file containing information about the smallest numbered pit that each block is part of.
2. Use the re-blocking program—apply the pit list file produced in step 1 to each one of the simulated block models. This will create a set of results files.
3. Produce cross-sections for the incremental pit shells.
4. Generate the summary pit information for the two pits. The analysis must be carried out for each one of the available simulated models. Derive the information referent to the incremental volume by subtracting the cumulative mining physicals (ore and metal quantities) and economic values (Net Value, processing cost and mining cost) between the two successive pit shells.

The above procedure is similar to the procedure used in the first section of this paper. The difference is that here the analysis is limited to two specific pit shells. The increment from pit 26 to pit 27 contains approximately 53 Mt of rock and is located in the southern end of the pit. Table 1 presents the results obtained by the analysis of the pit increment.

The risk profile on the contained ore shows a range between 5.7 and 6.2 Mt, with an expected tonnage of approximately 5.9 Mt. Low ranges of variation are also

**Table 1** Risk profile for mining physicals and economic parameters for the increment between pits 26 and 27

	Expected	Minimum	Maximum	Range
Ore ( $\times 1000t$ )	5925	5706	6222	516
Metal (oz)	341,739	309,451	362,982	53,531
Grade (g/t)	1.95	1.93	1.98	0.05
Mcost ( $\times 1000\$$ )	-103,594	-103,716	-103,521	195
Pcost ( $\times 1000\$$ )	-70,783	-74,285	-68,238	6047
Net value ( $\times 1000\$$ )	7381	-8164	17,685	25,849

shown for the risk profiles on grade, metal content and costs. The main issue here is in relation to the Net Value, which has a chance of being negative. Its risk profile goes from approximately \$-8.2 M to \$17.7 M. The reason for the increase in the risk profile the mining cost associated to a high stripping ratio ( $\sim 9$ ), which makes the Net Value oversensitive to possible variations on the recovered gold. It is important to notice that the risk profile indicates an expected Net Value for this increment of \$7.4 M. In fact, only one out of 15 simulated models presented a negative value for the Net Value. The results indicate a relatively low uncertainty in tonnages and grades contained between pits 26 and 27. However, this relatively low uncertainty becomes a critical issue due the high stripping ratio which makes the increment's Net Value very sensitive to grade uncertainty as well as gold price.

Several cross-sections have been generated to show the pit region relative to the increment between pits 26 and 27. These sections show the incremental shells, the current pit design and ore blocks contained inside the increment. The main conclusions drawn from the analysis of these cross-sections have four components. First, the major difference between the incremental Whittle pit shells \$550/oz and \$560/oz corresponds to a region located at the southern end of the pit. Most of the incremental ore blocks have an expected value inside the range of 1.5–2.5 g/t. Moreover, most of the incremental ore blocks have more than 60% chance of being above the cut-off. The increment contains a high quantity of waste and the pit design has considerably more waste than pit shell 27.

## Conclusions

The goal of this work was to illustrate different applications of risk analysis on the effects of grade uncertainty to various aspects of pit optimisation and design. Four cases have been carried out to illustrate different types of applications:

1. The first case consisted of an uncertainty analysis on pit optimisation results—Net Value, tonnage, grade and metal. The procedure consisted in applying a set of incremental pit shells, as produced by the pit optimisation process, to a set of simulated resource models. The subsequent analysis on each model produced a set of equally probably outcomes for the mining physicals and economic forecasts given the initial set of incremental pit shells.
2. The second case identified areas where grade uncertainty has major impact to the definition of the ultimate pit limits (upside/downside potential). Rather than developing a risk analysis on a given set of incremental pit shells, this procedure consisted in the generation of alternative sets of incremental shells, one set for each simulated model.
3. The third case aimed at quantifying the impact of grade uncertainty to tonnage, grades, metal and Net Value of two different mining scenarios for a given cut-back. The main objective was to evaluate if one of the scenarios was any better in terms of the compromise between Net Value and risk exposure.

4. The fourth case consisted of a risk analysis related to pit increments. The objective of this analysis is the quantification of uncertainty on the ore blocks driving the increment between two successive Whittle pit shells.

The results were presented in two steps:

1. first, each optimisation output was evaluated in terms of contained ore, grade, metal and pit value; and
2. the second step of the analysis consisted on the generation of a series of cross-sections.

These cross-sections were taken over all optimised models and included the actual pit design. Several conclusions have been drawn from these graphs indicating areas of upside and downside potential.

This paper presented a set of procedures that enable mine planning engineers to carry out a series of analysis, which can be used to evaluate the sensitivity of incremental pit shells and pit designs to grade uncertainty. The results obtained from the analysis have shown to provide valuable information, which can be used to develop mining strategies that are risk resilient in relation to grade uncertainty.

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