Programs to Use Geostatistical Models in Mine Planning

Behrang Koushavand, Hooman Askari Nasab and Clayton V. Deutsch

In this paper, all steps that are needed to transfer geological uncertainty to mine planning are described. The block models that are generated by GSLIB codes are used. These files first imported to the Gems and Whittle. The final pit is calculated using Lerchs and Grossman algorithm and the results are exported to the Matlab. A FORTRAN code called MSQ_F reads the GSLIB output files and Whittle's mine sequence file. It removes all blocks outside of the final pit and generates a single file that is readable by MATLAB. MATLAB codes are used to generate optimum schedule. All the programs and the steps are clearly documented and illustrated with pictures.

Introduction

Mine planning is a process to find a feasible block extraction schedule that maximizes net present value (NPV) and it is one of the critical processes in mining engineering. Also, there are some technical, financial and environmental constraints that should be considered in mine planning. Whittle (Whittle, 1989) defined open pit mine planning as 'Specifying the sequence of blocks extraction from the mine to give the highest NPV, subject to variety of production, grade blending and pit slope constraints'.

Based on decision making, there are three time ranges for production scheduling: long-term, medium-term and short-term. Long-term can be in the range of 20 - 30 years. This period is broken into several medium-term periods of 1 - 5 years. Medium-term schedules give more detailed information that allows more accurate design of the ore extraction from a special area of the mine, or information that would allow the substitution or the purchase of the required equipment and machinery. Medium-term schedules are also broken down into 1 – 6 month periods (Osanloo et al., 2008).

Numerical modeling is a robust method to quantify geological complexity. A limited number of samples are collected as a representation for the domain of interest and they are used to build numerical models. These samples are considered at the point scale. There may be some additional secondary information such as geophysical attributes that are mostly assumed at block scale.

A geologic block model is obtained by dividing the deposit into a very high resolution three-dimensional grid at the point scale. On the other hand, block dimensions for mine planning are selected according to the exploration drilling pattern, ore body geology, mine equipment and anticipated operating conditions. The sizes of the blocks used in mine planning are a function of the selective mining unit (SMU). The high resolution grid is up-scaled to get the right block scale values. Arithmetic averaging of point scale grades provides the up-scaled SMU grades (Figure 1).

Geostatistical modeling

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

1. Analyze the correlation structure: This investigates whether a transformation of the vertical coordinate system is required or not, in order to determine the true continuity structure of the deposit. Determination of the correct grid dependents on the correlation grid that yields the maximum horizontal continuity.
2. Decluster the drillhole data distribution: The relevant statistics must be deemed representative of the deposit prior to modeling. Any or a combination of cells, nearest neighbour and/or

declustering by kriging weights should be employed to determine the summary statistics that are representative of the field. DECLUS program is used to get the 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. Data are transferred into normal scores using the NSCORE program; afterwards, the directional experimental variograms are calculated using the GAMV program. VMODEL program was used to fit an anisotropic variogram with two nested spherical structures.
4. Perform the estimation and cross validation using Kriging as checking against simulation results: Using kriging, cross validation provides a quality control check on the estimation (and also simulation) parameters.
5. Generate multiple realizations using Sequential Gaussian Simulation (SGS) (Isaaks, 1990): This method is the means of constructing uncertainty models. SGS is one of the most commonly applied geostatistical simulation algorithms applied in the natural resources sector. It has been extensively validated and provides a measure of the local and global uncertainties, which is not afforded from Kriging.
6. Check simulation results against the input data and compare the results against the Kriged models. The quality of geo-model is checked by histogram and variogram reproduction and also a grade tonnage curve of Kriging. At this stage, simulation realizations can be very useful.
7. The block dimensions for mine planning are selected according to the exploration drilling pattern, ore body geology, mine equipment and anticipated operating conditions. The sizes of the blocks used in mine planning are a function of the selective mining unit (SMU). The high resolution grid is up-scaled to get the right block scale values. Arithmetic averaging of point scale grades provides the up-scaled SMU grades. Program Blockavg is used to get upscaled block model for each realization at separate file.

Gems, Whittle and MSQ_F

Each of realizations, kriging and Etype block model are imported to Gems (Gemcom Software International, 1998-2008). Also this software needs rock type block model and topography surface. Figure 2 to Figure 12 shows the steps that should be taken to import GSLIB file formats to the gems. Figure 13 shows the Kriging block model (ore blocks) at 3D view. After importing and creating all profiles at Gems, each block model is exported to the whittle (Gemcom Software International, 1998-2008). Figure 14 to Figure 33 show the steps of whittle software to define pit shells, push backs, final pit, schedule etc. Whittle used Lerchs and Grossman algorithms (1965) to generate final pit.

Whittler's generated schedule is exported to an ASCII file format called MSQ file (mining sequence file).This file have all the blocks inside the final pit. This file is used to follow the same schedule generated with one block model for example Kriging block model with other realization to understanding the effect of grade uncertainty at production schedule. The program called MSQ_F is GSLIB like FORTRAN code that has been developed for this purpose. Figure 34 shows the parameter file for MSQ_F. The first line is the file name of MSQ file generated by Whittle. Next lines are the number of ore rock types and the name of ore rock types. If there are two ore rock types, the name of each of them should be written at separate lines. Next line is the block model that is going to follow. At this example, the realization number one is going to follow at schedule generated by Kriging. The next line is the number of column that simulated values are at the R1.out file. The next three lines are the grid definition information: the same format of GSLIB output files. Next 8 lines shows the parameters that are needed to follow the schedule. For each line there are some descriptions. Last two lines are the output files. First one is the quick report for each period such as input ore, waste tonnage, stripping ratio, cash flow etc. The last line is the output file that indicates which block should be extracted at which period and its portion. This file will be used at matlab codes. First three column of this file is the indexes of the blocks. Next columns respectively are the rock code, OreTonnage, WasteTonnage, RockTonnage,grade, OreValue, WasteCost and EBV.

Matlab Codes

There are five steps that should be followed in matlab:

1. Step01_Read: This is a matlab codes that reads the output file of MSQ_F and convert each realization to the matlab data base. The code name is “do.m”. There are some input parameters that are documented clearly. A matlab structure is define for each block model. For each block there are x,y and z coordinates, ix,iy and iz indexes, Tonnage, EBV, Orevalue etc. The code reads the output file of MSQ_F file and convert the information to the matlab .mat file format. These files are used at next steps.
2. Step02_Adjacency_Matrix: At this step, one block model is used to generate the adjacency matrix of precedent arcs. Kriging block model or ETYPE is mostly used. This matrix controls the precedence of extraction of the blocks. It is a N by N matrix , N is number of blocks. For each block, the blocks that are needed to be extracted before are indexed. The “adjacency_matrix.m” should be run and it generates an output file named “inputToMILPBlocks.mat” and a graph shows the matrix. The name of the input block model should be “Blocks.mat”. Therefore user needs to copy the block model file generated from previous step and copy it to this folder and change the name to “blocks.mat”
3. Step03_Clustering: In this step, the similar blocks are aggregated to generate mining cuts to reduce the number of variable. Matlab’s Cmean method is used. “clustering_mining_cuts.m” should be run as a function. The input parameter is the maximum number of clusters. It uses blocks at same lever and their x and y locations, grade and ebv to find similar blocks. The input file is “inputToMILPBlocks.mat” generated at previous step. The output file is “inputToMILPcuts.mat”.
4. Step04_addSims: In this section, all realizations are added to the “inputToMILPcuts.mat” the output file is “inputToMILPcuts2.mat”. The code “doit.m” shoud be run. It reads all the block model files generated at step one and calculated average values inside each mining cuts for each realization.
5. The next step is to add some parameters to the “inputToMILPcuts2.mat” these parameters are: numOfPeriods, interestRate, mcMax and mcMin (min and max of mining capacity for each period) , oreGradeMin and oreGradeMax (min and max of input grade to the mill for each period and element), Prestriping (number of pre striping years), numOfElements, numSims(number of simulation realizations), elementsProcessed (the index of elements that are going to be processed), pcMax and pcMin (the min and max capacity of processing plants), OverCost and UnderCost (the cost of over and under production).
6. There are four different method to solve the LP. “Main.m” should be run. At all codes the all the blocks insider the final pit are forced to be extracted at end of mine life. This option can be canceled at “mip.m” code.
    - Step05_MILP_Cuts_Reserve: Generate schedule not using simulation realizations such that all the blocks inside the final pit should be extracted.
    - Step05_MILP_Cuts_Reserve - Mining Limit: Generate schedule without using simulation realizations such that there are no limits to mining capacity.
    - Step05_MILP_Cuts_Reserve - Proc Limit – NoOver: This folder The MILP generate a schedule using the entire block inside the final pit and simulation realizations such that none of realizations generate over production. Therefore there are hard constraints on maximum limit production which are applied to all of realizations.
    - Step05_MILP_Cuts_Reserve - Proc Limit – NoUnder: The same as above without having under production at specific periods. This method will not generates feasible solution most of the time. Because it is impossible to generate a schedule that does not have under production for all realization at all periods. Therefore user should limit the hard constraints to one or two periods at early years of production.
7. There are six different methods to solve the LP using simulation realizations and penalize the possible over and under production:

- Step06_MILP_Cuts_Reserve_Sims: generate schedule using kriging and simulation realizations. All the blocks are removed at the end of mine life.
- Step06_MILP_Cuts_Reserve_Sims - Mining Limit: This code is used kriging and realizations. There are no constraints on mining limit.
- Step06_MILP_Cuts_Reserve_Sims - Proc Limit: The hard constraints on processing limit for kriging block model has been removed and the same as other realizations, the penalty is applied for over and under production for kriging.
- Step06_MILP_Cuts_Reserve_Sims – StockPile: This method generates schedule using kriging and simulation realizations with considering stockpile. The stockpile is used to stocks any probable over productions and material are processed at next period. Stockpile is applied to realizations only.
- Step07_MILP_Cuts_Reserve_var: This method is used variance coefficient method. The method is described paper 308 CCG annual meeting 2011.
- Step08_MILP_Cuts_Reserve_No NPV: This code is minimizing deviation from target production and there is no maximization on NPV. The reason of using this code is to find out lower limit of cost of uncertainty. The NPV of this method is the minimum NPV of all previous methods.

Conclusion

The steps that are needed to be taken for moving from Geostatistical simulation model to the mine optimization and planning stage are described at this paper. Clustering method is needed to reduce the number of variables. Therefore final pit should be known before to satisfy the slop constraint of the pit. That is the reason that whittle software is used. For future works, pushbacks that are designed at whittle will transferred to the optimization stage and Matlab codes.

References

Deutsch, C.V., Journel, A.G., 1998, GSLIB geostatistical software library and user's guide. Oxford University Press, New York.

Gemcom Software International, I. 1998-2008. Whittle strategic mine planning software (Vancouver, B.C., Gemcom Software International).

Isaaks, E.H., 1990. The application of Monte Carlo methods to the analysis of spatially correlated data, Ph.D. thesis, Stanford University. PhD. Stanford University, Stanford, CA.

Lerchs, H., Grossmann, I.F., 1965, Optimum design of open-pit mines. The Canadian Mining and Metallurgical Bulletin, Transactions LXVIII, 17-24.

Leuangthong, O., Schnetzler, E., Deutsch, C.V. 2004. Geostatistical Modeling of McMurray Oil Sands Deposits. In 2004 CCG Annual Report Papers, Deutsch, C.V., ed. (Edmonton, Centre for Computational Geostatistics), pp. 309-301 to 309-310.

Osanloo, M., Gholamnejad, J., Karimi, B., 2008, Long-term open pit mine production planning: a review of models and algorithms. International Journal of Mining, Reclamation and Environment 22, 3-35.

Whittle 1989. The Facts and Fallacies of Open Pit Optimization. In Whittle Programming Pty Ltd.

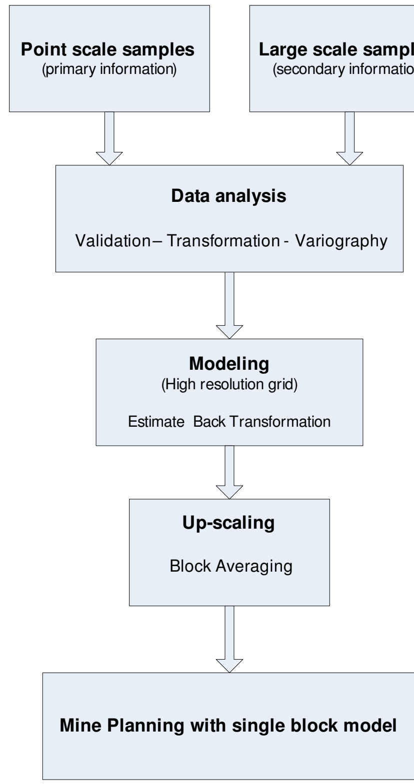


Figure 1. Traditional mine planning stages.

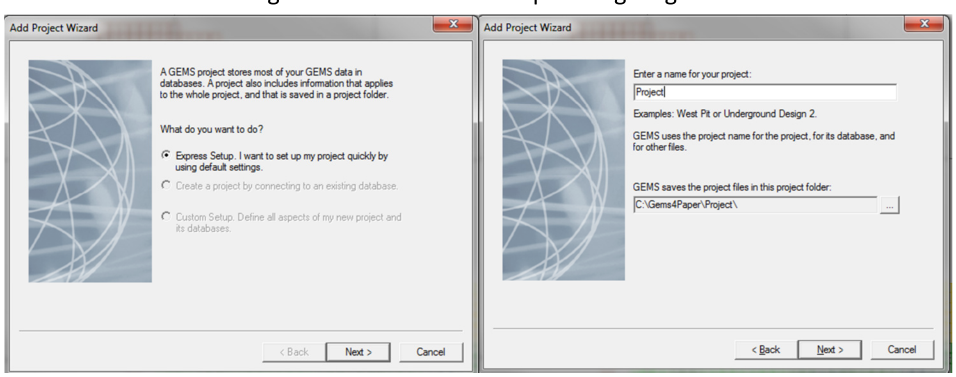


Figure 2. Create a project at Gems and choose a name for the project

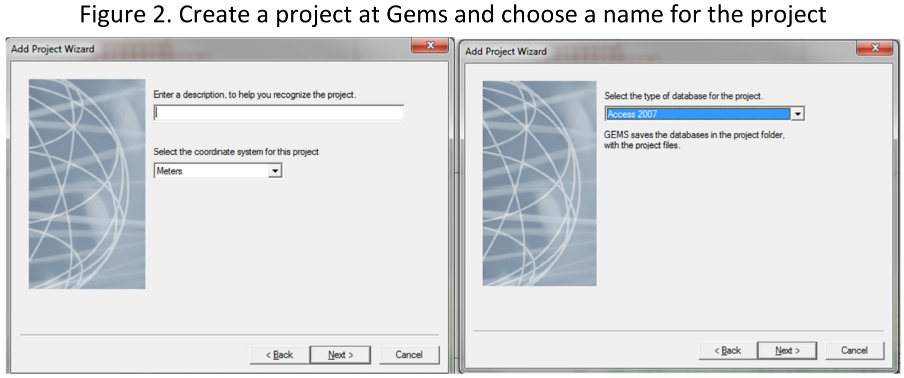


Figure 3. Choose the scale and the database type

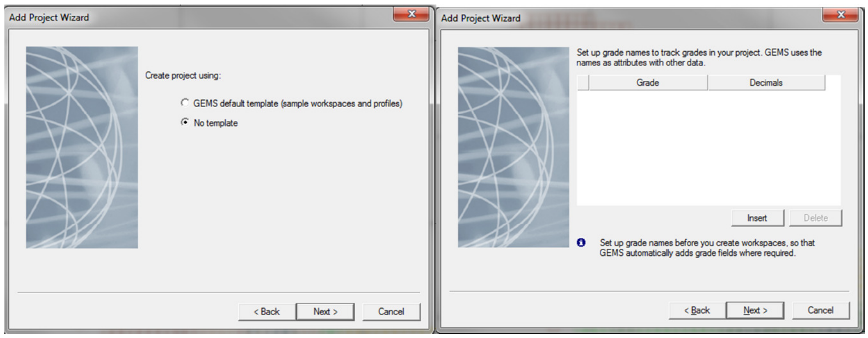


Figure 4. Create the project with No template option and insert the name of Element of interest

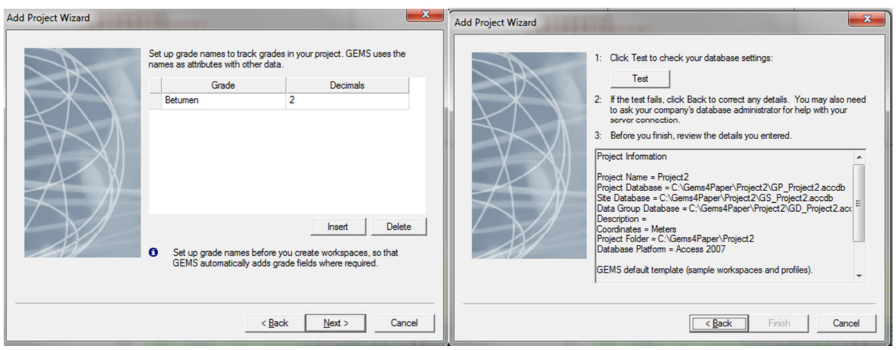


Figure 5. Final step at creating the project

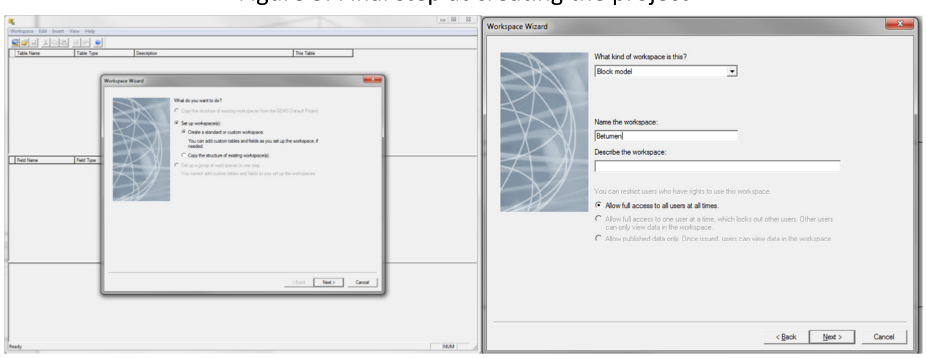


Figure 6. Create a block model and choose the name

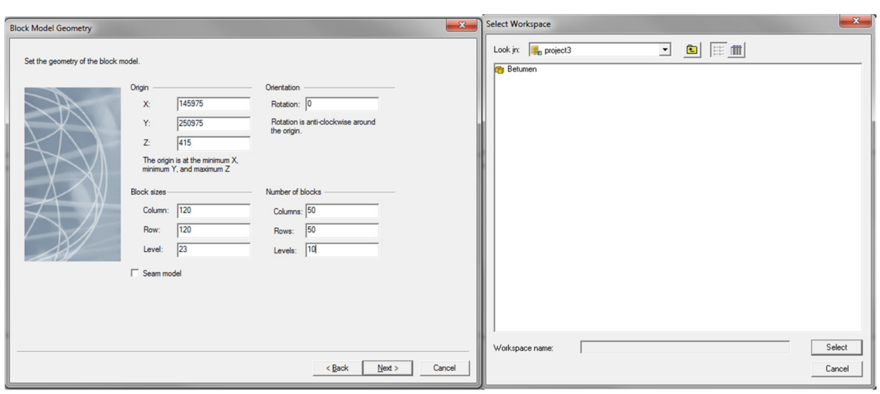


Figure 7 Define the number of blocks at each direction X,Y,Z , the origin of the blocks and size of them.

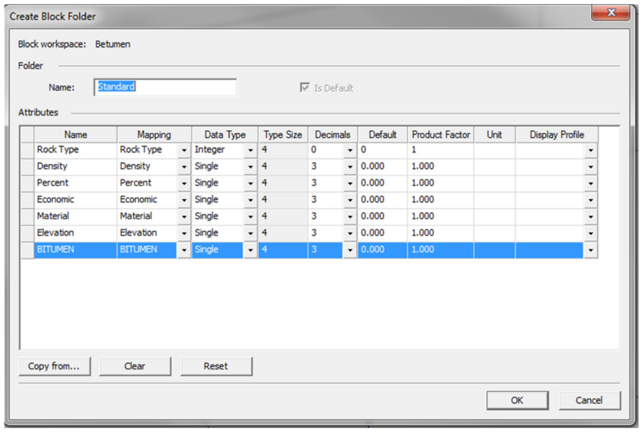


Figure 8 open the block model

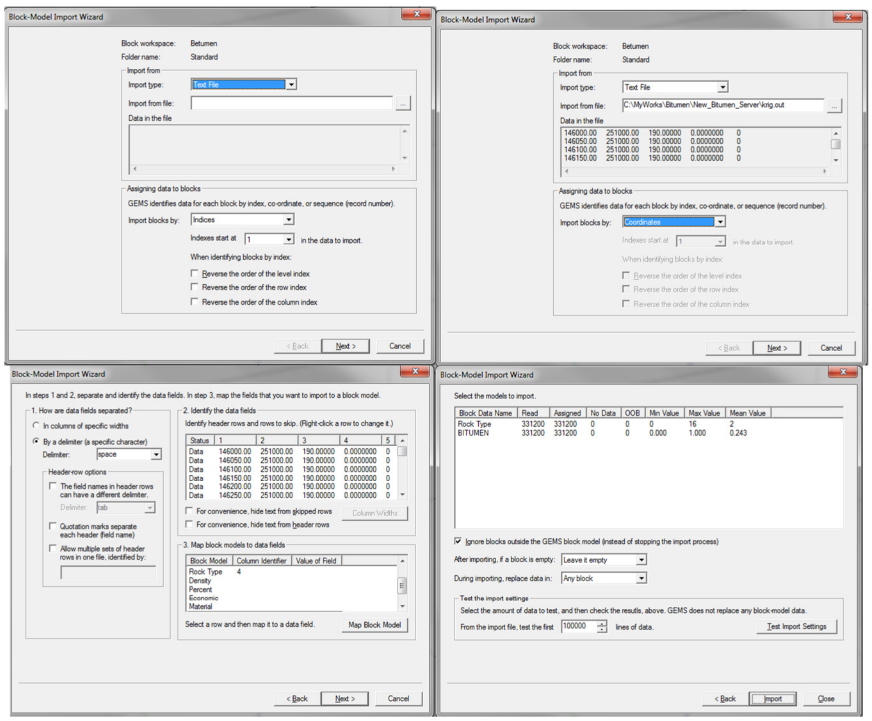


Figure 9. Import GSLIB text files to the Gems data base.

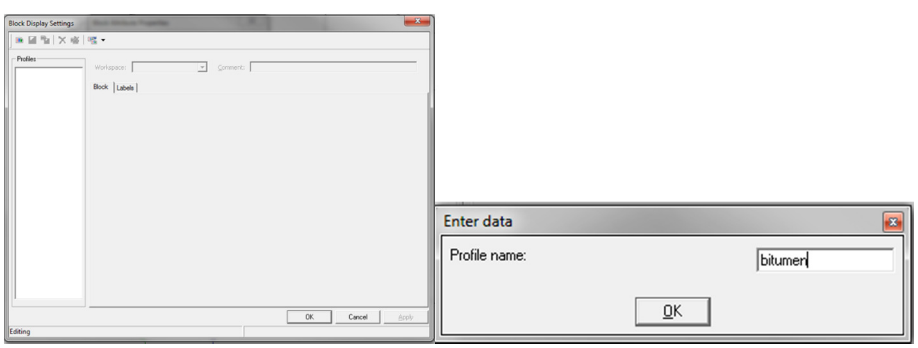


Figure 10 Create a display profile.

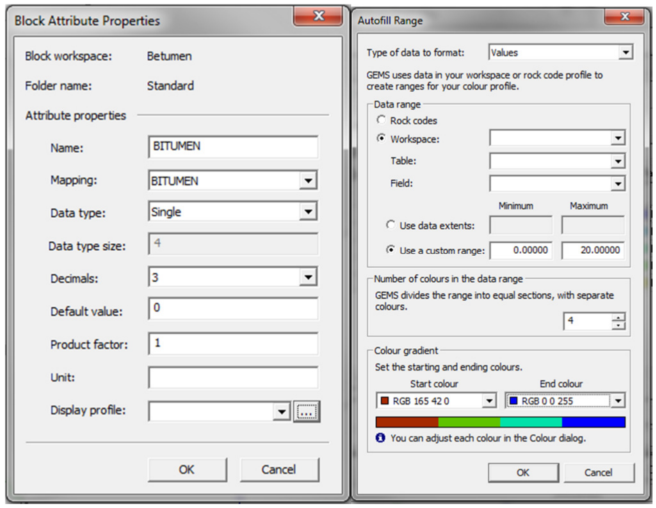


Figure 11 Create a color profile

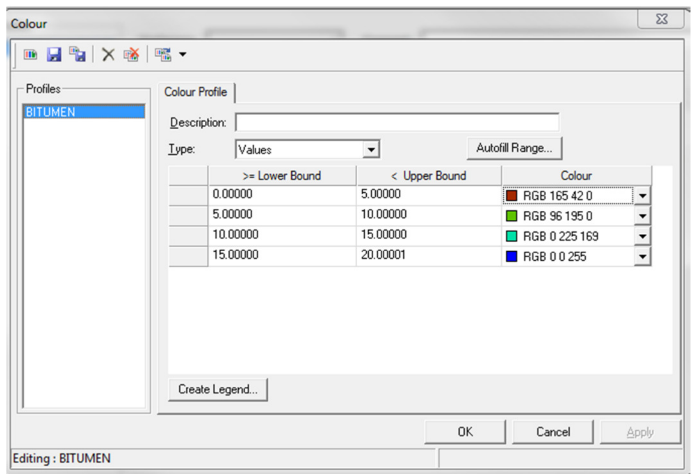


Figure 12 The Color profile that is created

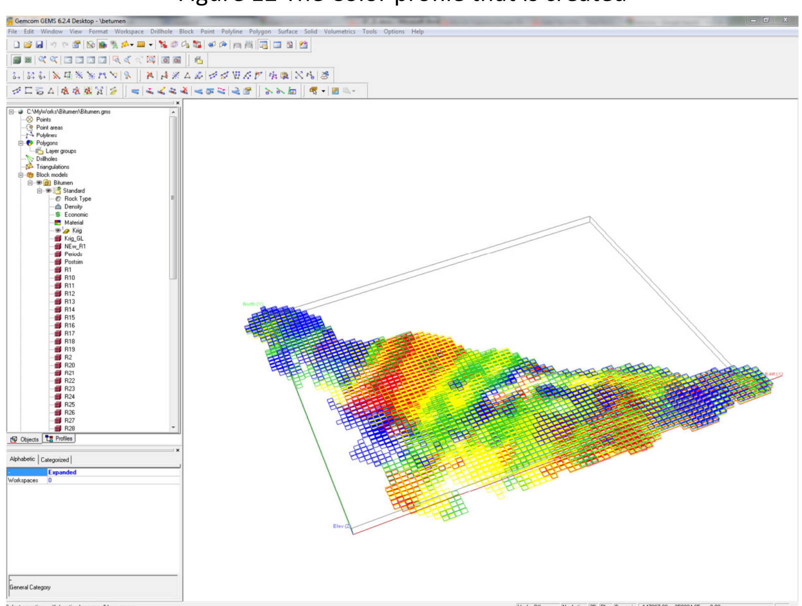


Figure 13. Gems Software Screenshot

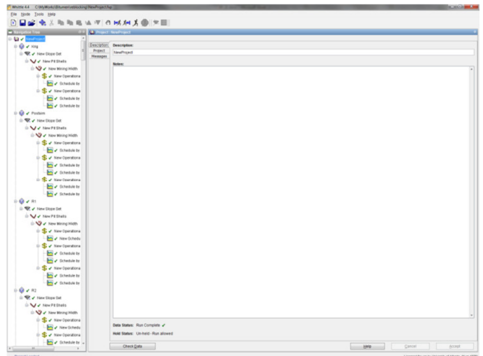


Figure 14. Whittle screen shot

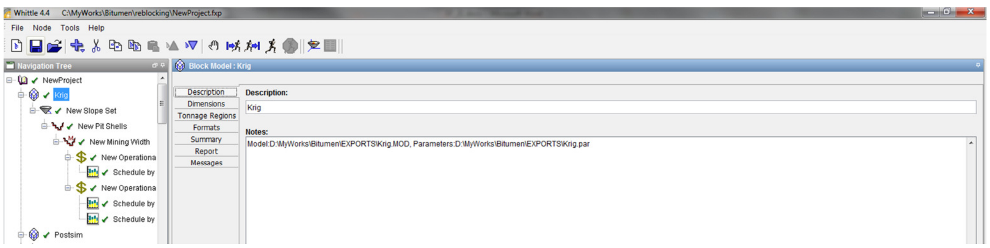


Figure 15. Create a project

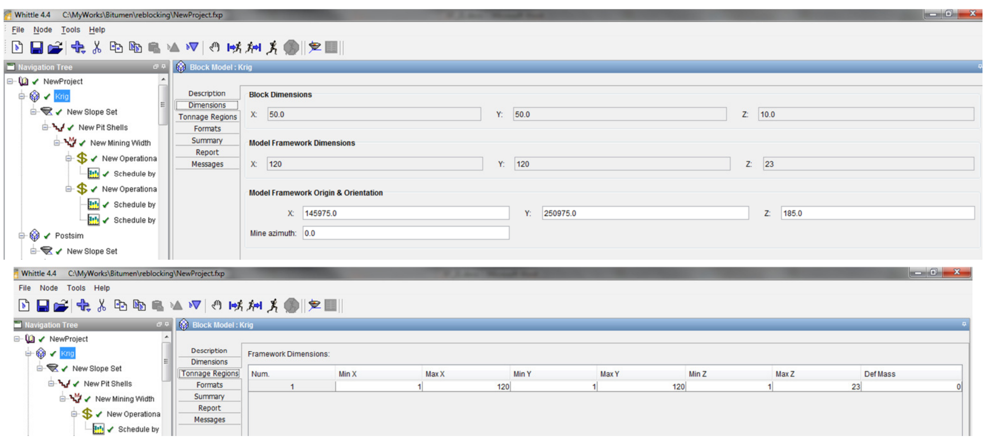


Figure 16. Check the imported model's grid definitions and dimentions

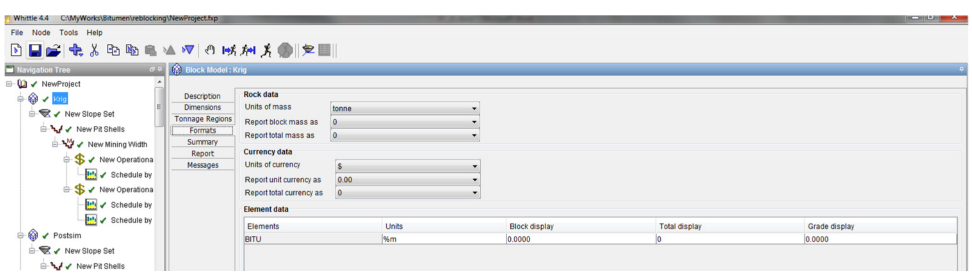


Figure 17. Change the Units to %m.

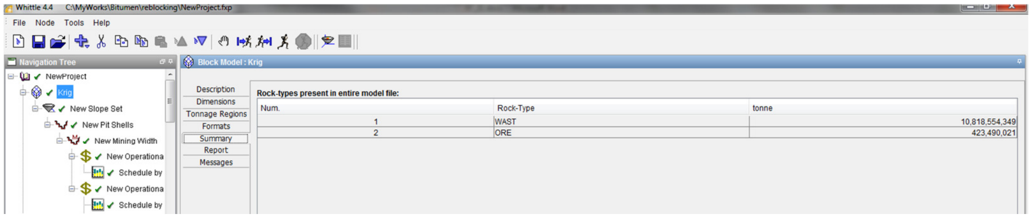


Figure 18. Total tonnage of Ore and Waste

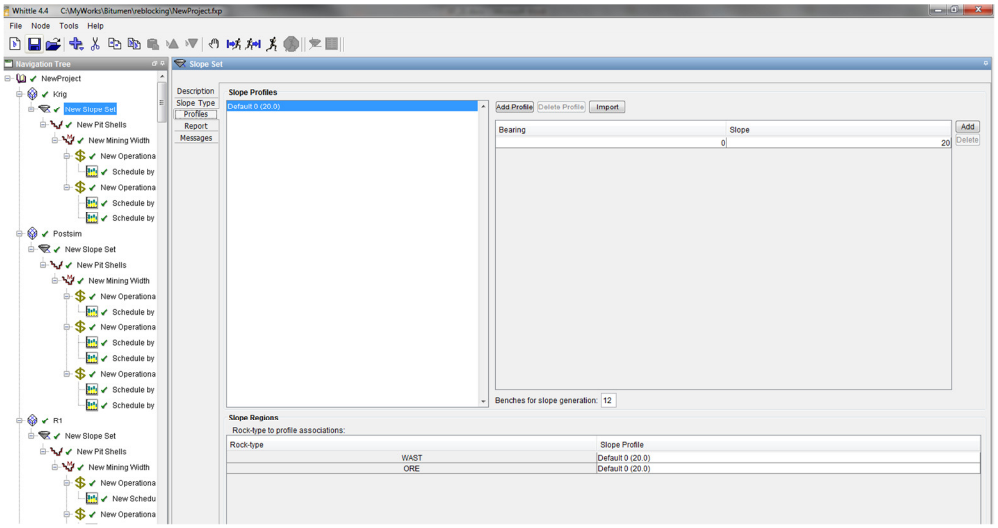


Figure 19. Define Slope of the Pit

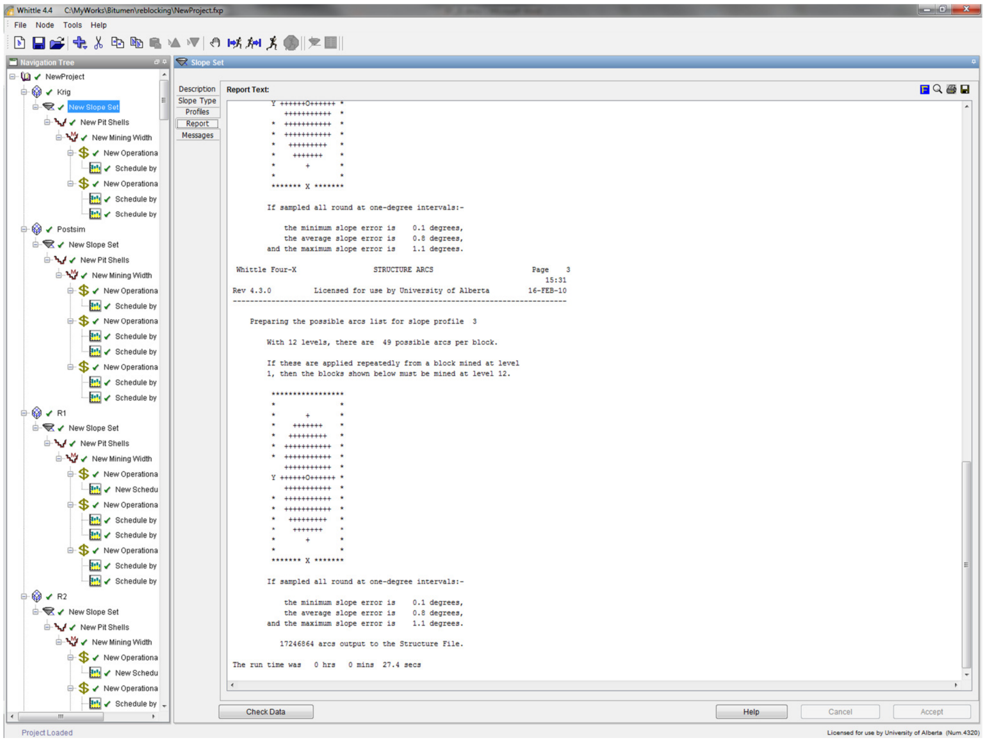


Figure 20. The report that shows the error of slop

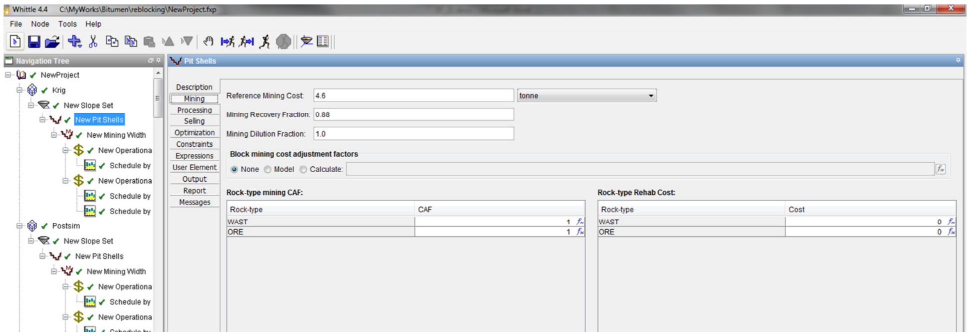


Figure 21. Create Pit shells. Mining Input Parameters

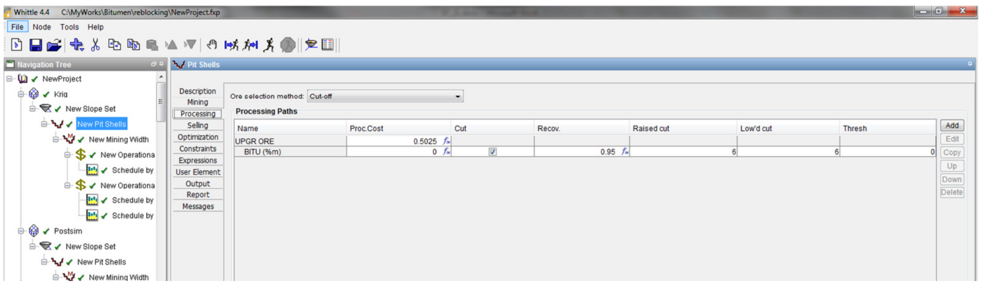


Figure 22. Create Pit shells. Processing Input Parameters

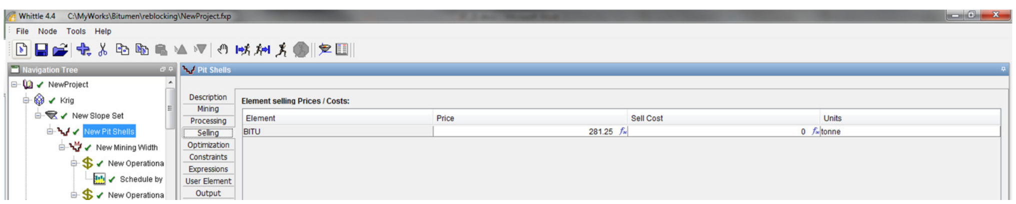


Figure 23. Create Pit shells. Selling Price of final product

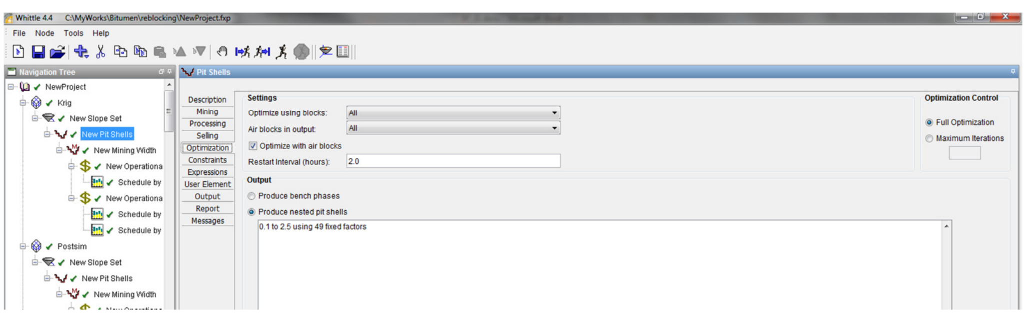
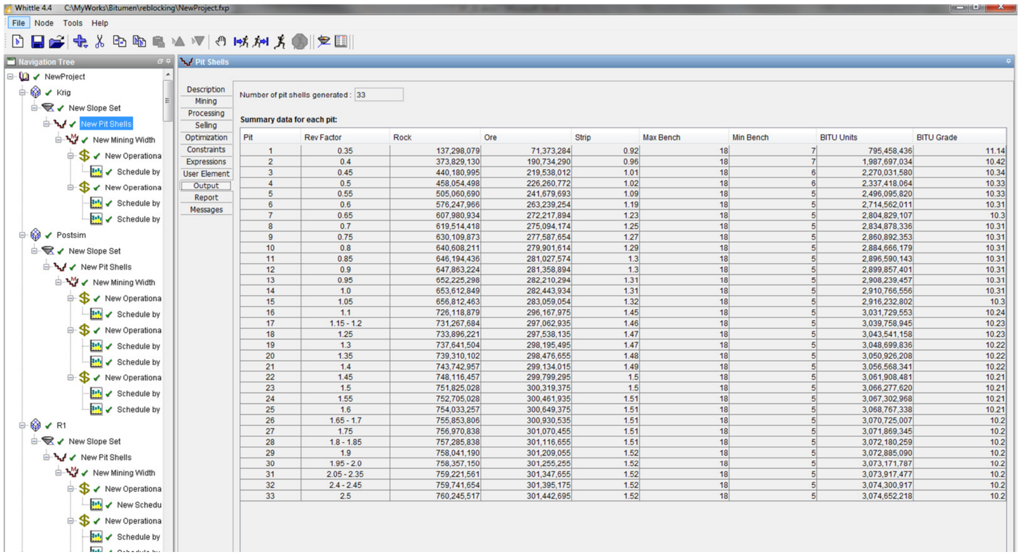


Figure 24. Create Pit shells. Revenue factor range definition



Pit	Rev Factor	Rock	Ore	Strip	Max Bench	Min Bench	BITU Units	BITU Grade
1	0.35	137,298,079	71,373,284	0.92	18	7	795,458,436	11.14
2	0.4	373,829,130	190,734,290	0.96	18	7	1,987,697,034	10.42
3	0.45	440,180,995	219,538,012	1.01	18	6	2,270,031,580	10.34
4	0.5	458,054,498	226,260,772	1.02	18	6	2,337,418,064	10.33
5	0.55	505,060,690	241,679,693	1.09	18	5	2,496,095,820	10.33
6	0.6	576,247,966	263,239,254	1.19	18	5	2,714,562,011	10.31
7	0.65	607,980,934	272,217,894	1.23	18	5	2,804,829,107	10.3
8	0.7	619,514,418	275,094,174	1.25	18	5	2,834,878,336	10.31
9	0.75	630,109,873	277,587,654	1.27	18	5	2,860,892,353	10.31
10	0.8	640,608,211	279,901,614	1.29	18	5	2,884,666,179	10.31
11	0.85	646,194,436	281,027,574	1.3	18	5	2,896,590,143	10.31
12	0.9	647,863,224	281,358,894	1.3	18	5	2,899,857,401	10.31
13	0.95	652,225,298	282,210,294	1.31	18	5	2,908,239,457	10.31
14	1.0	653,612,849	282,443,934	1.31	18	5	2,910,766,556	10.31
15	1.05	656,812,463	283,059,054	1.32	18	5	2,916,232,802	10.3
16	1.1	726,118,879	296,167,975	1.45	18	5	3,031,729,553	10.24
17	1.15 - 1.2	731,267,684	297,062,935	1.46	18	5	3,039,758,945	10.23
18	1.25	733,896,221	297,538,135	1.47	18	5	3,043,541,158	10.23
19	1.3	737,641,504	298,195,495	1.47	18	5	3,048,699,836	10.22
20	1.35	739,310,102	298,476,655	1.48	18	5	3,050,926,208	10.22
21	1.4	743,742,957	299,134,015	1.49	18	5	3,056,568,341	10.22
22	1.45	748,116,457	299,799,295	1.5	18	5	3,061,908,481	10.21
23	1.5	751,825,028	300,319,375	1.5	18	5	3,066,277,620	10.21
24	1.55	752,705,028	300,461,935	1.51	18	5	3,067,302,968	10.21
25	1.6	754,033,257	300,649,375	1.51	18	5	3,068,767,338	10.21
26	1.65 - 1.7	755,853,806	300,930,535	1.51	18	5	3,070,725,007	10.2
27	1.75	756,970,838	301,070,455	1.51	18	5	3,071,869,345	10.2
28	1.8 - 1.85	757,285,838	301,116,655	1.51	18	5	3,072,180,259	10.2
29	1.9	758,041,190	301,209,055	1.52	18	5	3,072,885,090	10.2
30	1.95 - 2.0	758,357,150	301,255,255	1.52	18	5	3,073,171,787	10.2
31	2.05 - 2.35	759,221,561	301,347,655	1.52	18	5	3,073,917,477	10.2
32	2.4 - 2.45	759,741,654	301,395,175	1.52	18	5	3,074,300,917	10.2
33	2.5	760,245,517	301,442,695	1.52	18	5	3,074,652,218	10.2

Figure 25. Created Pit shells with different revenue factors

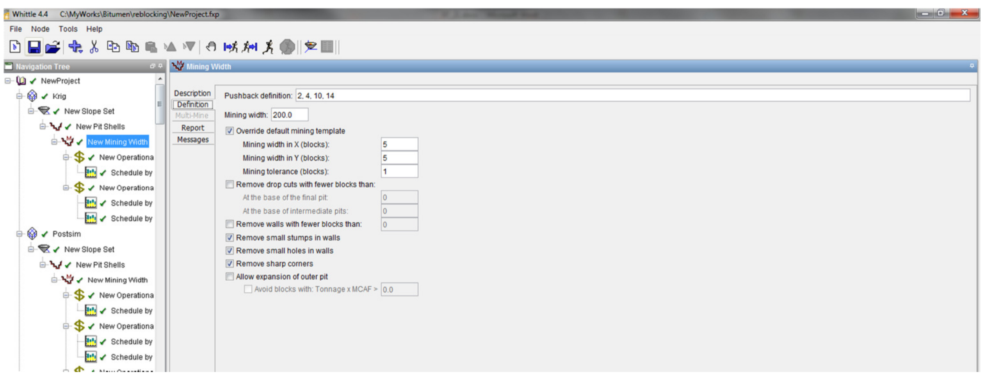


Figure 26. Choose Push backs

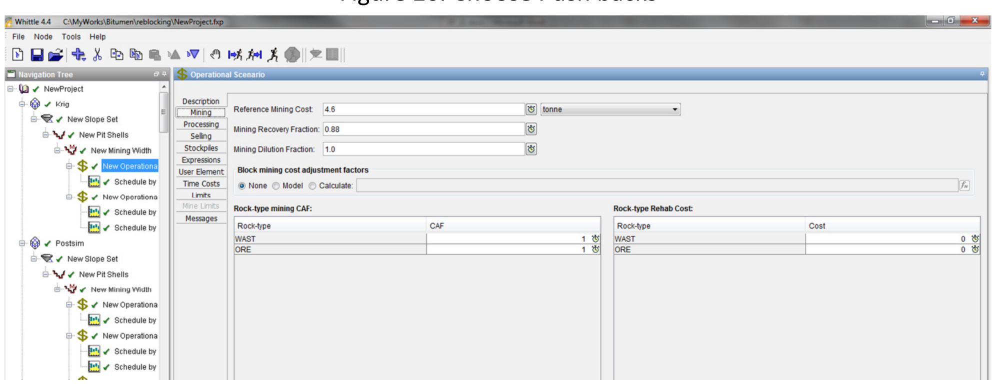


Figure 27. Create schedule: Mining Input parameters

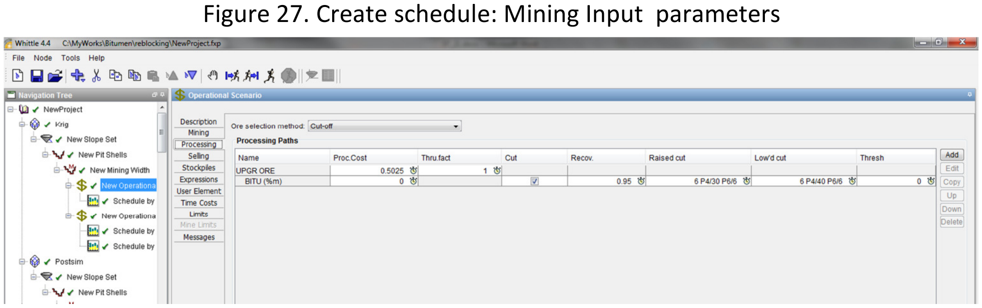


Figure 28. Create schedule: Processing Input parameters

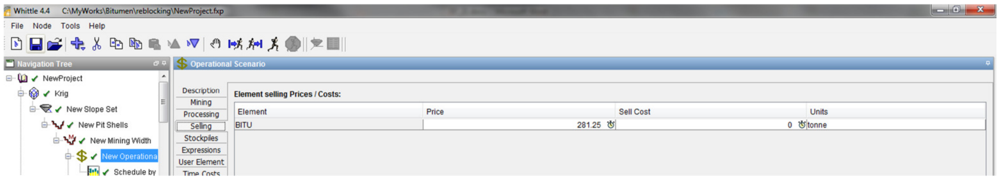


Figure 29. Create schedule: Selling Price

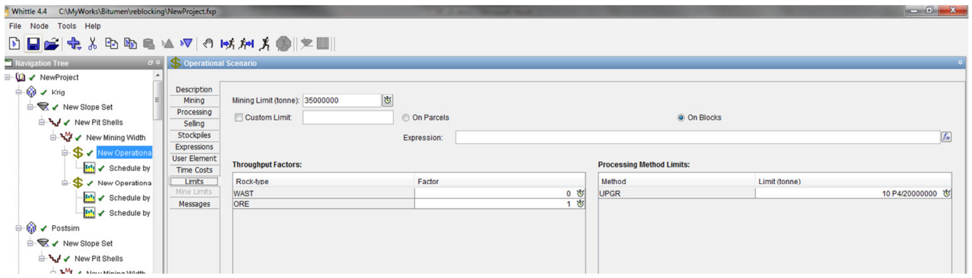


Figure 30. Create schedule: Mining and processing limits

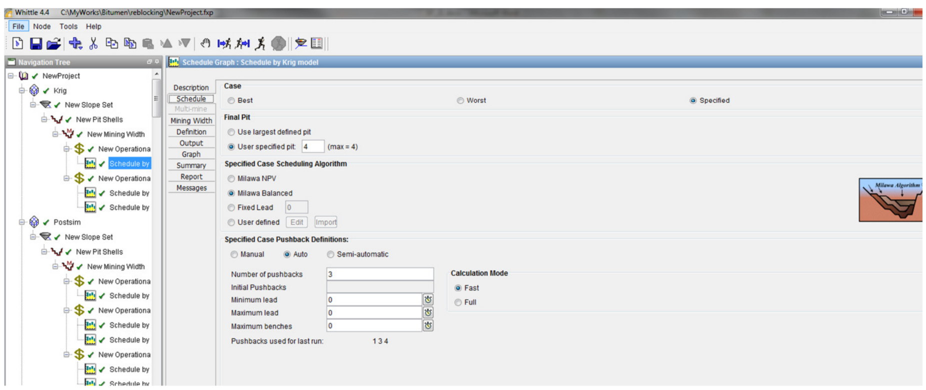


Figure 31. Create schedule: Optimization parameters

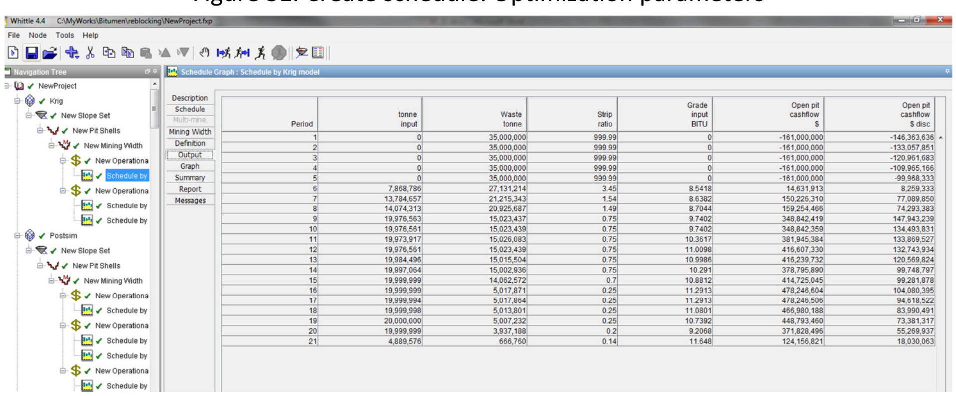


Figure 32. Created schedule

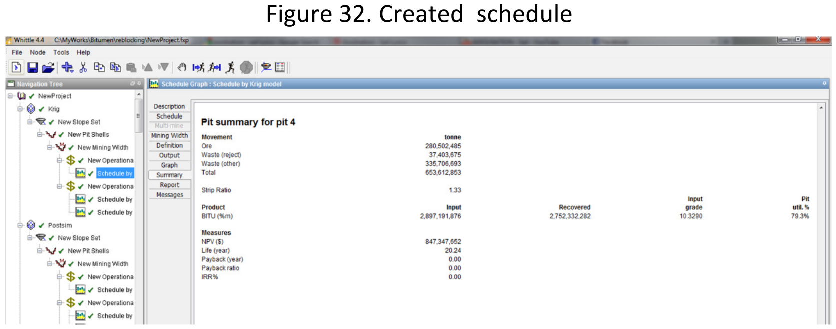


Figure 33. Final report

```
                 Parameters for MSQ
              ***********************

START OF PARAMETERS:
Krig.msq                        -MSQ file
1                               -number of rocktype that are ore
ORE
R1.out                          -file with blocks
4                               -   column for variable and weight
120   146000.0     50                 -nx,xmn,xsiz
120   251000.0     50                 -ny,ymn,ysiz
23    190.0        10                 -nz,zmn,zsiz
4.6                              -Mining Reference Cost
0.88                             -Mining Recovery
0.5025                           -Processing Costs
0.95                             -Processing Recovery
281.25                           -Selling price($ per %mass)
6                                -Cutoff
0.1                              -InterestRate
2                                -Pre-striping (years)
R1.csv                           -file with output
Blocks_01.csv                    -file with sequences
```

Figure 34. Parameter file of Program MSQ_F

Period	tonne input	waste tonne	Strip Ratio	Grade input	cashflow	discounted cashflow	RejectedOre
1	0	35001067	9999	0	-1.6E+08	-1.5E+08	0
2	0	34997808	9999	0	-1.6E+08	-1.3E+08	0
3	0	34998206	9999	0	-1.6E+08	-1.2E+08	0
4	472432	34526610	73.08	6.66	6.79E+08	4.64E+08	2354490
5	498257.8	34503708	69.25	6.66	7.25E+08	4.5E+08	2483200

Figure 35. The quick report of MSQ_F.

32	31	5	1	47520	6480	54000	6.75088	833263.5	248400
31	32	5	1	47520	6480	54000	7.60357	941527.5	248400
32	32	5	1	47520	6480	54000	7.20186	890523.4	248400
33	32	5	1	47520	6480	54000	6.84176	844802.4	248400
30	33	5	1	47520	6480	54000	8.5612	1063115	248400
31	33	5	1	47520	6480	54000	7.72666	957155.9	248400
...									

Figure 36. The report of MSQ_F for each block