Block sequencing analysis and importance of mining recovery and dilution in mine planning

by

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ORIGINALITY STATEMENT

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ABSTRACT

A critical step in open pit mining is determining the appropriate sequence of block extraction, which has a significant impact on mining profitability. The open-pit mining block sequencing issue, which emerges at this stage, is described to find the optimal sequence in which blocks should be extracted following numerous physical and technological restrictions. Moreover, mine planning should take mining recovery and dilution into account and engage fully in planning and optimization processes. The optimal mining block sequencing provides the highest net present value (NPV) of the project. **This paper proposes a mathematical model and software computation for the open-pit mine block sequencing in open pit mining operations. The primary goal was to analyze sequencing, the ultimate pit limit, pushbacks, and scheduling simulation findings, which correspond to real-world mining projects in Datamine Studio NPVS, and compare with optimistic and pessimistic scenarios.** The results showed the highest Net present value is observed in Pit no. 88 in the optimistic scenario (+20% in price) – 914,612,423 $, while the lowest NPV results were in the pessimistic scenario (-20% in price) - 356,593,171 $ in Pit no. 82 Moreover, possible optimization improvements of block sequencing, ore recovery and dilution will be addressed. To demonstrate the superior attributes of the enhanced model, an open-pit gold mine case study was presented. The combination of direct block sequencing and the traditional method allows for improving NPV results by 0.43% which is regarded as an achievable outcome. Mine planning software must develop and adapt to meet current requirements and improve innovative solutions to existing block sequencing problems.

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1. INTRODUCTION

1.1 Background

The most widespread and oldest way of extracting rich material from the earth is open-pit mining. Numerous researchers have been drawn to the operation to explore different areas such as production planning, truck-shovel allocations, risk analysis, and grade mixing. Numerous heuristic, meta-heuristic, and mathematical programming approaches have been used to enhance the functioning of these operations. Their objectives are to maximize profit, decrease expenses, and optimize resource usage or the mining operation's result. Additionally, the mine planning issue has been investigated throughout a variety of periods. Typically, long-term to short-term plans are developed based on varying degrees of detail. Long-term plans often address bigger units of production and determine when and where to extract materials. On the other side, short-term plans focus on smaller units and make more precise choices on production levels, blending, and truck-shovel allocations.

The former - strategic mine planning, starts with the development of a discretized mathematical model of the ore body, referred to as a block model. Typically, a deposit of interest is split into thousands of three-dimensional (3D) rectangular cubes, referred to as a block model. The coordinates of a block show easting (x), northing (y), and elevation (z) of the block (Mousavi et al., 2016). Each block is allocated several geological properties based on data gathered from exploratory drill holes. These attributes include ore and waste grades, rock types, and rock densities. Then, each block within the block model is assigned to a particular order, which is called block sequencing. The block sequencing problem is described as identifying the appropriate sequence for extracting blocks under a variety of practical and technological limitations. Several restrictions are considered in the block sequencing problem, including precedence relations, equipment limits, mineral processing capacity, and grade control. For various time horizons, the block sequencing issue may be addressed. Mousavi et al. (2016) claim that the mine block sequencing issue may be characterized as determining the order in which blocks should be extracted from the mine and assigned to their proper destinations. Generally, the mine block sequencing model is composed of the following components: blocks, processing circuits, stockpiles, excavators, time horizons, and mining regulations. Apart from which blocks will be mined and when they will be extracted, strategic mine planning deals with where they will be extracted. Destinations represent not only physical locations but also block processing and treatment options. Mills, trash dumps, leach pads, and stockpiles are all examples of block destinations.

The open pit mining block sequencing issue, which emerges at this stage, is specified to establish the optimal sequence in which blocks should be removed according to the various physical and technical restrictions. Another crucial aspect of block sequencing is the determination of the optimal cut-off grade for the mining blocks. The cut-off grade has a direct impact on the economic viability of mining operations for the course of the project's life. The approach of using a high cutoff grade to get a greater overall NPV for a specific project begins with a high cutoff grade. Increased cutoff grade results in greater average grades per ton of ore throughout the earliest stages of the mining sequence; accordingly, higher average grades are realized based on the deposit's grade distribution (Moosavi & Gholamnejad, 2016). The cutoff grade indicates the amount mined, processed, and lastly, the product generated in the refinery for selling in each mining sequence. The success of the project highly depends on the cutoff grade established. As a result, optimizing the cutoff grade is critical in terms of mine life.

Block sequencing is difficult due to the generally large number of blocks, as well as the number of periods, limitations, and inherent complexity. Even though appropriate block sequencing may increase the economic worth of the project, there are also some problems to consider while planning the open pit mine. During extraction, processing, and other mining activities some uncertainties may appear through mining recovery and dilution. Dilution raises the mill's operating costs by increasing the amount of material that must be milled. Apart from its direct effect on a mine's short-term revenue, dilution results in major changes in other aspects, lowering the project's total worth in the long term. Another aspect to mention is the mining recovery of the project. The primary elements affecting the ore recovery ratio include mining technique, blasting, seismic events, rock bursts, grade control, geology, and other factors such as rock drilling and rock support.

1.2Objectives of the Thesis

Main Objectives

There is a great impact of block sequencing on both the mine production aspect and the economic aspect as well. Thus, it is important to sequence blocks in the correct way to maximize the Net Present Value (NPV) of the project. The thesis paper presents an analysis of block sequencing approaches of open pit mines worldwide and suggests possible improvements in the block sequencing model by providing software and design optimization. The software simulation was also produced to represent the block sequencing in open pit mine, which correspond to real-world mining projects. The software algorithm simultaneously produces optimal cut-off grade strategies, sequence of extraction, and scheduling of the project. The main objective was to evaluate and compare three scenarios (base, optimistic, and pessimistic) of the project considering price and mining/processing costs changes. In the discussion section, these outcomes of the software will be evaluated using approaches of other open pit mines.

1.3 Justification of the R&D

This is a significant and complex topic with a multidisciplinary approach that may need evaluation of economic, statistical, and optimization factors concurrently. Economic scheduling directly reflects consideration of time-value-of-money impacts. As technologies developing throughout the years, it is important to implement an appropriate sequencing and scheduling methods.

2. LITERATURE REVIEW

2.1 BLOCK SEQUENCING

Numerous scientific papers provide distinct optimization approaches in mining block sequencing model problems. As was mentioned before, the mine block sequencing problem is defined as determining the sequence in which blocks should be extracted to minimize stockpiling costs, including rehandling and holding costs, and to satisfy all physical and strategic constraints, including precedence relationships, mining capacity, processing demands, and grade requirements. Additionally, the mine block sequencing solution should optimize material movement from the mine to the processes and stockpiles, as well as from the stockpiles to the processes. However, before extracting mining blocks, ore and waste materials should be determined. To differentiate ore and waste blocks we use a given equation:

$$Economic\ Block\ Value\ =\ Revenue\ -\ Mining\ Cost\ -\ Processing\ Cost\ (1)$$

If the difference between the revenue and the operational cost is negative, we classify the block as waste and compute its extraction cost as simply the product of the amount of waste and the associated mining cost. Otherwise, the block qualifies as an ore block. Based on this classification, we categorize each ore block as destined for the processing plant and each waste block as destined for the dump. From that, we define a new term – cut-off grade for the open pit. A cut-off grade is used to represent the difference between ore and waste in a certain mineral deposit. In general, cut-off grade refers to the minimal quantity of valuable minerals that must occur in a unit of material (e.g., one tone) before it is transported to the processing facility (Mousavi et al., 2014). The cut-off grade of the open pit significantly affects the mine sequences. Moosavi and Gholamnejad (2016) assume that cutoff grade optimization is a multidisciplinary process that considers metal prices, mining costs, milling costs, the processing plant's capacity, mining capacity within the mining operation, mining sequence, deposit grade distribution, and consequent cash flow. Moreover. The authors claim that maximum present value and constant cut-off grades are incompatible and as a result, numerous attempts have been made to develop a computerized procedure for optimizing cutoff grade while taking mining sequence into account, including utilizing Penalization, Lagrangian relaxation, 4D-Network relaxation, Dynamic programming, and Genetic algorithm.

There are two primary strategies for completing block sequencing. The first is based on the Lerchs-Grossmann algorithm's (LG) production of Nested Pits. This technique utilizes a revenue component to control the size of the pits by discounting the price in the block valuation, followed by various scheduling algorithms. Due to the difficulty of solving the overall open pit planning problem in a single step, the traditional planning process (used by the industry since the 1960s) divides the main problem into several sub-problems, such as determining the ultimate pit limit, generating pushback, scheduling, blending, and optimizing the cut-off grade. Over time, strategies for optimizing these individual options have been developed. For example, Lerchs and Grosmann (1965) developed an algorithm that ensures optimality when determining pit limits to maximize undiscounted cash flow. Additionally, they proposed a way of constructing nested pits to generate pushbacks (P. Campos et al., 2018). However, P. Campos et al. (2018) adds that this approach has three shortcomings: (1) it uses a fixed cut-off grade that is dependent on an arbitrary delineation between waste and ore; (2) it employs stochastic prices to determine the nested pits; and (3) it applies the piecemeal approach to the entire optimization problem, omitting the temporal interaction of resource requirements. Since the extraction sequence is determined, this sequence might stay unchanging for many years. Johnson et al. (2011) agree that commodity prices are unknown, and the company must determine in real time whether the ore grade is high enough to justify further processing in preparation for sale or to simply waste the block.

There are several approaches to optimize block model sequencing. They could be categorized as software optimization and design in a model of the block sequence. According to Brickey and Eurek (2014), most commercial solvers, such as CPLEX (IBM 2011), solve integer algorithms using the branch-and-bound (B&B) technique. Our solution approaches are aimed to improve the solver's functionality by using the open pit block sequence problem's unique structure. The author provides the following solution methodologies attempt to reduce the solution time for instances of (CPIT) by (1) tightening the formulation; (2) solving the linear programming (LP) relaxation of the integer program at the root node with the proper algorithm and corresponding algorithmic settings; (3) reducing the problem size through variable elimination; and (4) providing the optimizer with an initial integer feasible solution. The first could be enhanced by tightening the restriction set and substituting a collection of variables indicating the period before which a given block must be mined for the set of decision variables determining when a specific block must be mined. In the second case a CPLEX software, for example, has a network simplex method that can solve the LP more quickly when a large component of the constraint matrix of the LP contains a network structure. The third solution provides a variable elimination approach. The author finds that the variables y_{bt} indicate whether block b should be extracted at period t. Periods t' signify that the variable $y_{bt'}$must have the value 0 in any conceivable solution, enabling us to therefore exclude $y_{bt'}$ from the formulation.

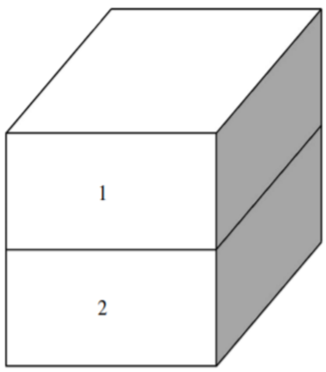

Figure 1. Two block model (Brickey & Eurek, 2014).

Figure 1 illustrates a simple 2 block model. Because block 1 must be mined prior to block 2, it is mathematically impossible (i.e., practically impossible) to extract block 2 during period 1. As a result, the value of the variable y_{21} must equal zero in any conceivable solution; consequently, having y_{21} in the model is pointless. This approach minimizes the time; thus, performance of block model sequence is increased as a result. All in all, the author emphasizes that the variables of the upper blocks are important, minimizing the engagement of the lower blocks. Then, Brickey and Eurek (2014) contradicts that "lower bounds can be important, too: the scale and nature of production and processing operations in an open pit mine imply that large set-up costs accrue if operations are stopped and started repeatedly. Placing lower limits on production and processing reduces the potential for such effects". Despite its importance to open pit block sequencing, it increases the time of performance. The author adds that a five-period test issue with no lower limits takes 176 seconds to solve using CPLEX, but 3,688 seconds when lower bounds are included.

Another technique is based on direct block scheduling (DBS), in which blocks are assigned extraction times directly through an underlying mathematical optimization problem. While this strategy is theoretically better, it suffers from the computing complexity associated with addressing mathematical problems, which may be quite large (P. H. A. Campos et al., 2018).

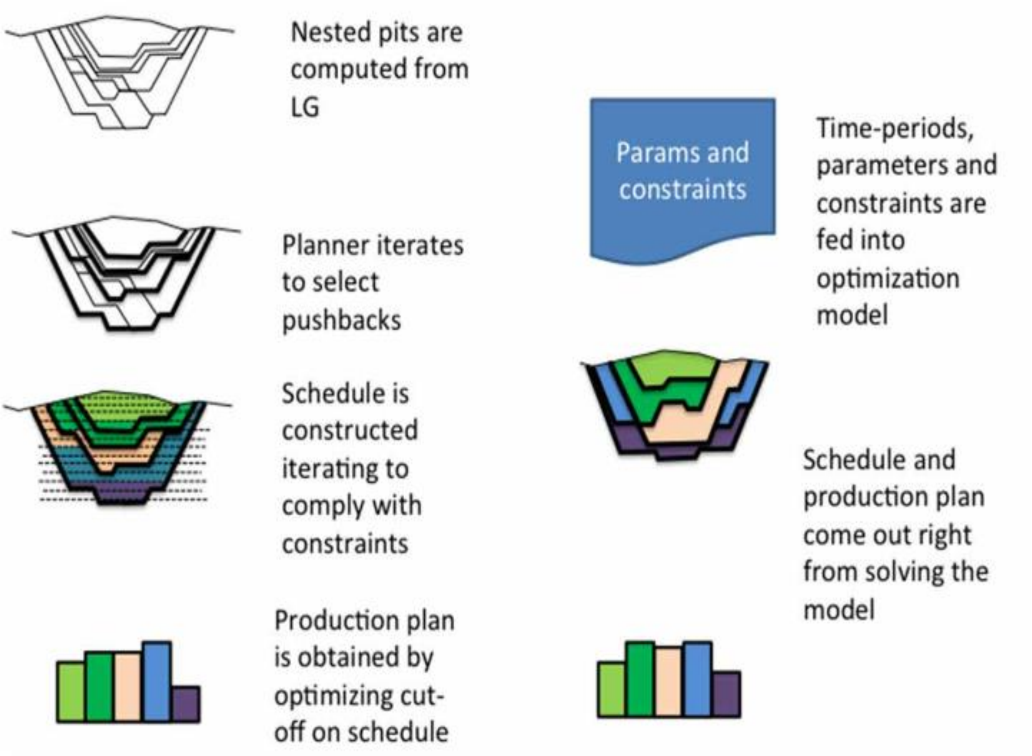

Figure 2. Traditional methodology versus direct block scheduling (P. H. A. Campos et al., 2018).

Figure 2 illustrates two primary methods for mine scheduling. On the left, is the conventional method, which depends on LG to build nested pits from which pushbacks are selected, and then production is scheduled. On the right is the DBS technique, which feeds all parameters and restrictions into an optimization model that generates a schedule and a production plan. It is critical to note that, the traditional technique requires the planner to assure compliance with constraints, optimization models cannot provide solutions that violate a constraint.

Another thing to mention is the importance of integer programming for open pit mines. Fricke (2006) defines that the main objectives of the integer programming are to optimize all aspects of a mine operation, from mine to plant to market; optimize life-of-mine schedules; optimize intermediate and short-term schedules following the life-of-mine schedule, and provide an efficient method for updating schedules as conditions change or new information becomes available. However, Cullenbine et al. (2011) establish that this integer programming can be extremely difficult to solve, because: (i) a mine model may have from 10^4 to over 10^6 blocks, (ii) the time horizon may have T = 20 periods or more, and (iii) the resulting model may have millions of variables and constraints. Integer programming is also used in the ultimate pit limit problem. Moreover, Mousavi et al., (2014) add that "the first gap is the lack of MBS models for a short-term horizon and the second gap is the lack of efficient solution approaches that are suitable for this problem".

In addition, some authors provide other approaches to optimize open pit block sequencing and scheduling. Alah and Nogholi (2015) introduce Lagrangian relaxation and claim that the primary goal of this approach is to loosen up the subject by eliminating certain constraints, referred to as side constraints, and including them into the objective function through adjusted Lagrangian multipliers. Side constraints are limitations that make the issue very difficult to solve. Therefore, integrating some complicating constraints into the objective function could be done through the penalty factor. Instead of linear programming relaxation, the Lagrangian relaxation approach may be utilized to establish a lower limit on a branch and bound algorithm. Moreover, Tolouei et al. (2020) add that for mixed-integer programming problems, the Lagrangian relaxation (LR) approach is well-known as a viable mathematical solution. This approach is given in long term production scheduling (LTPS) using Lagrangian multipliers, which relax system constraints and present them to the objective function. After that, the relaxed problem is broken down into smaller, more manageable sub-problems that may be solved using dynamic programming by independent components. The Lagrangian relaxation could be also implemented in the sliding time window heuristic method. According to Cullenbine et al., (2011), the sliding time window heuristic (STWH) is based on solving a sequence of mixed-integer programs that have fixed variables in early periods, a full model representation in at least one middle period, and a relaxed representation in later periods. The use of Lagrangian relaxation is critical for computational efficiency. The author provides a method in which variables of mine production become more flexible and agrees that Lagrangian relaxation is a crucial factor in mine sequencing. Other authors provided a direct block sequencing approach, which is more enhanced since extraction times for blocks are determined directly by an abstract mathematical optimization method. Nevertheless, it suffers from the computational complexity required to solve huge mathematical problems and could not perfectly replace Lerch-Grossman technique.

2.2 MINING RECOVERY AND DILUTION

Mining projects are inherently uncertain and risky. This is because market circumstances, resource models, and mining parameters like tonnages, grades, and dilution all remain unpredictable. To mitigate investment risk, mining corporations devote significant time and money in studies that forecast grades and tonnages, as well as mining conditions and costs. Due to the difficulty of monitoring certain critical design characteristics, such as dilution, some elements might be overlooked. Revenues are calculated using the tonnage and grade of ore established during the mine design. To compute the tonnage and grade, a resource model, dilution, and mine recovery parameters are used. It could be observed that the involvement and consideration of mining recovery and dilution is crucially vital in the mining industry. The following section is going to provide the possible solutions on optimizing the mining recovery and dilution. One thing to mention is that a high early cut-off grade will result in significant ore loss, while a low late cut-off grade would result in excessive waste rock and raise mining costs (Zhang et al., 2021). Dilution is a term that refers to waste material that is not separated from ore during the mining process and is mined alongside ore. This waste is combined with ore and sent to a processing facility. Dilution increases ore tonnage while lowering the grade. **Dilution is defined as the ratio of waste mined and supplied to the mill to the total amount of ore and trash processed. It is often stated as a percentage. The dilution could be expressed as the equation (2) below**:

$$Dilution = \frac{Tonnage\ of\ Waste}{Tonnage\ of\ Ore + Waste} \times 100\% \tag{2}$$

Dilution occurs in two distinct places when referring to a mining block. Occasionally, waste inclusions or low-grade pockets of ore occur inside a mining block and are unable to be separated and are unavoidably mined together with the mining block. This process is referred to as internal dilution. Internal dilution is difficult to prevent, if not impossible. Internal dilution occurs in varying degrees in various kinds of deposits. Internal dilution is influenced by lithology and grade distribution. External dilution, sometimes termed contact dilution, refers to waste that is mined outside of the orebody inside the mining block. External dilution varies according to geology, orebody form, drilling and blasting procedures, operation scale, and equipment size. This is the form of dilution that is controllable with the use of appropriate equipment and mining methods. Figure 3 demonstrates a mining block in an open pit mine bench with several sorts of dilutions.

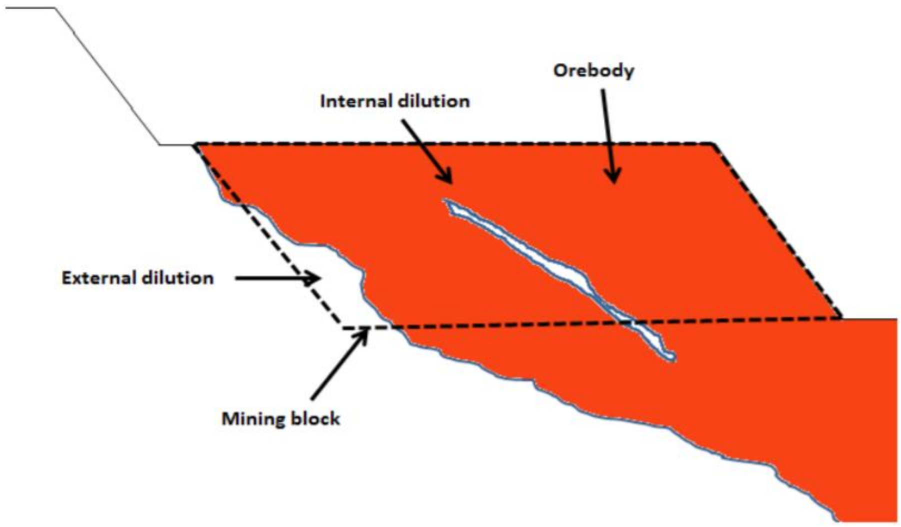

Figure 3. Open pit scheme and types of dilution (Ebrahimi, 2013).

It is crucial to understand the impact of the dilution to the economic segment of the open pit mine project. Ebrahimi (2013) claims that one of the primary outcomes of dilution is a decrease in the grade of mill feed. A lower feed grade equates to a lower revenue. Dilution may lower the grades of marginal grade ore to the point where processing becomes uneconomic; in other words, dilution can transform an ore block into waste block. The equation 2 below may be used to determine the feed grade after dilution.

$$Feed_g = \frac{ore_g + waste_g \times dilution}{1 + dilution} \quad (3)$$

Secondly, dilution results in a loss of energy and resources utilized in the processing plant to treat the waste part of the feed. As a consequence, the unit operating cost of the mill rises according to the dilution factor. For instance, in a project with an expected processing cost of $18/t, a 10% dilution implies that $1.80 is spent processing trash in the mill for every ton of feed. For a 30,000 ton per day plant, this quantity of dilution equates to a daily loss of $54,000. Thirdly, occupying part of the processing capacity by sending waste rocks to the plant prolongs mine life. As a result, it delays cashing the value of mineable resources on time as planned. A longer mine life lowers the net present value (NPV) and internal rate of return (IRR). For example, consider a mine that has the potential to generate $20M/year net revenue by milling a certain amount of ore for up to 10 years. This is after $100M initial capital investment. Assuming a 10% dilution the mine life increases to 11 years from 10 years. With a simple calculation, it is possible to compare mine economics for two cases of mining operation, with dilution and without dilution. For this example, there will be a 21.0% decrease in NPV (at 10% discount) and an 8.6% decrease in IRR after 10% dilution. Although dilution cannot be avoided, it can be quantified and then controlled. In most cases, quantifying dilution is so challenging that calculating it will become the main part of the solution. In mining operations, to calculate dilution the information obtained from samples on conveyor belts (after crusher) can be compared with resource/reserve models that are developed using drill data. This is the best way of calculating the actual dilution occurring in a mine. The accuracy of the calculation of course depends on the accuracy of sampling and resource modeling. In the case of mining studies, where no operation data are available, suitable techniques must be used to estimate dilution. Quantifying dilution during the study stage is necessary to have a better economic evaluation of the project. In addition to achieving a more accurate economic evaluation, quantifying dilution helps to improve mine design. If the study shows significantly high dilution, it is a starting point to mitigate it by changing the mine plans. Dilution can be reduced by adjusting the mine design and operation-related factors to best match the deposit-related factors. For example, by reducing bench height it may be possible to mine more selectively. Obviously, for this case, we must also realize that reducing the bench height will increase unit production cost due to the smaller scale of operation. The bottom line is that to improve the economy of a mine a series of factors such as bench height, selectivity, and production rate must be optimized together. This paper tries to introduce a technique for estimating dilution in open pit mines using computer software as well as proposing a standard procedure for the work. (Ebrahimi, 2013).

Marinin et al. (2021) introduce a possible solution for optimization in mining production. The Mine-to-Mill approach focuses on developing an integrated strategy for optimizing production, ore crushing, and subsequent grinding to minimize ore crushing costs and boost production profitability. The purpose of this connection is to optimize all stages of processing. In addition, the author claims:

"Mine-to-mill optimization's ultimate objective is to maximize the energy efficiency of rock breaking by maximizing blast fragmentation. In mines, crushing and grinding are among the most energy-intensive operations. Rock breaking accounts for around 30%–60% of overall energy usage in mines. As a result, this process has an effect on not just energy consumption, but also overall mining productivity. This process may be enhanced via the use of mine-to-mill optimization."

All mining and processing activities in gold mines require several consecutive steps. These steps should be mutually reinforcing, with one procedure influencing another. It is not sufficient to optimize each function independently to improve the whole process. The whole mineral extraction process should be considered. There are two distinct forms of mine-to-mill integration. One is operational, while the other is physical.

Operational integration focuses on the following:

• monitoring processes via the use of drill and shovel technologies.

• optimizing blast fragmentation.

• optimizing communication processes.

• improving factory monitoring, particularly of the handling system in the pit and ore.

Physical integration focuses on fragment size categorization, grade control improvement, sorting, and mill feed quality enhancement (Marinin et al., 2021).

2.3 CASE STUDY

2.3.1 Case study 1

Rosebel Gold Mines is a gold mine complex located in Suriname. The case study considers three deposits: Rosebel Mine, Pay Caro Mine, and Royal Hill Mine. Each deposit consists of blocks of 16 × 12 × 9 m, for a combined total of 1.07 million mining blocks: 0.26 million at Rosebel Mine, 0.38 million at Pay Caro Mine, and 0.43 million at Royal Hill Mine. The material uncertainty is quantified using 10 stochastic simulations of the gold grades per mine (LaRoche-Boisvert & Dimitrakopoulos, 2021). The drill and blast cost, loading cost, dump maintenance cost, and closure cost are all part of the mining cost, whereas the overall processing cost is broken down into processing cost, transportation cost, and storage cost to account for the various expenses involved with administration and maintaining capital with the many sorts of materials.

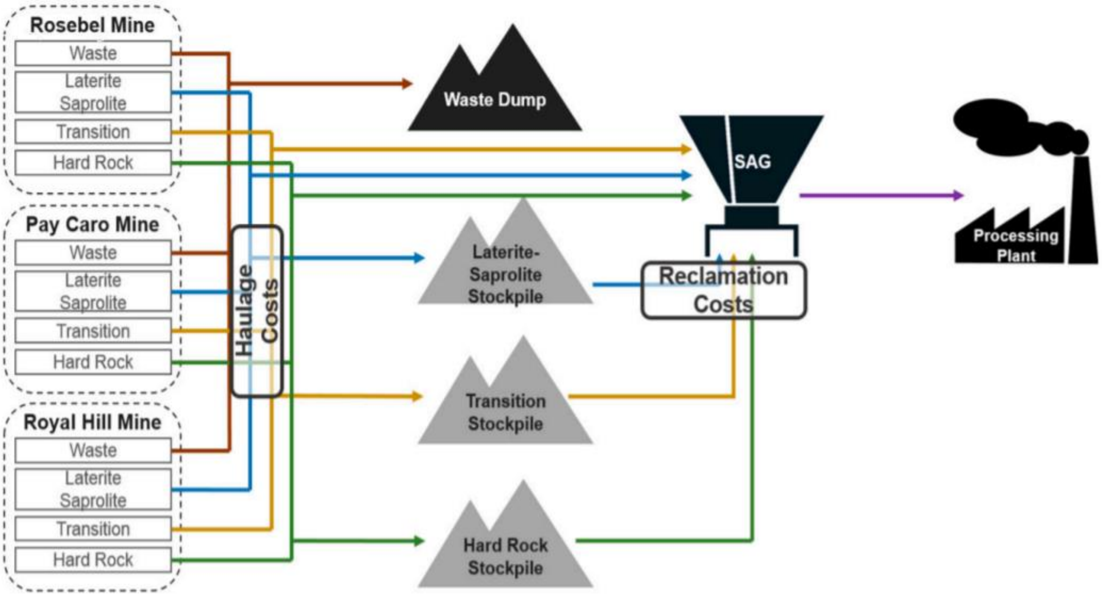

Figure 4. The schematics of the process of Rosebel gold mine complex (LaRoche-Boisvert & Dimitrakopoulos, 2021)

Figure 4 demonstrates the flow of the rock mass form three mines (Rosebel, Pay Caro and Royal Hill mine). The recovered ore material might be delivered straight to the processor or to the appropriate stockpile. In the early years, the laterite-saprolite material was stockpiled to a larger extent, and it was recovered over time. The hard rock material is stored to a higher degree at the conclusion of the mining complex's existence, whereas the transition material is rarely stockpiled. The SAG mill crushes ore that is recovered from stockpiles or supplied straight to the processor.

Table 1. Capacity and Scheduling constraints for developing scheduling (LaRoche-Boisvert & Dimitrakopoulos, 2021)

Constraints	Capacity
Mining Capacity (years 1–5)	67.3 Mt/y
Mining Capacity (years 6–18)	74.0 Mt/y
SAG Mill Capacity	876 h/y
Processing Capacity	8.83 Mt/y
Constraint	**Distance**
Smoothness	48 m
Max sink rate	63 m

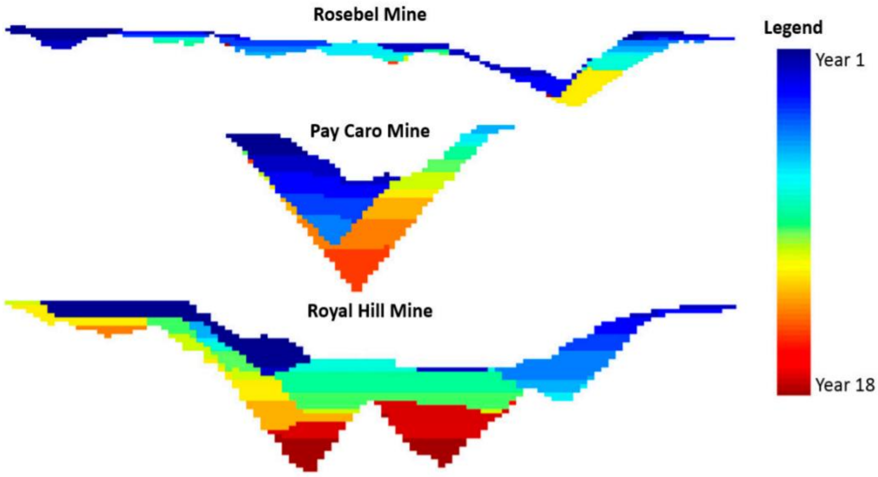

Figure 5. Stochastic life-of-asset production schedules at the three mines at the RGM mining complex (LaRoche-Boisvert & Dimitrakopoulos, 2021)

Figure 5 illustrates the schedule to produce three distinct deposits of the complex. The production schedule is developed by the constraints shown in Table 1.

2.3.2 Case study 2

The following case study was conducted by Saavedra-Rosas (2016). The examples were used from Minelib (Espinoza et al., 2013), library of test problems for open pit mining problems. Some of which corresponds to real-world mining projects. In terms of size, they were more suited for our research. Because of the cases is complicated and took a long time to compute (Saavedra-Rosas, 2016). This block model comprises 53 271, 30x30x30 m blocks, however this number may be lowered by removing blocks that are not accessible from the block model. A 45° slope angle and seven layers of precedence above a specific block determine the wall slope requirements.

Table 2. Main economic and technical parameters (Saavedra-Rosas, 2016).

Economic and technical parameters in the Marvin instance

Parameter	Value	Unit
Copper price	3.02	US$/lb
Gold price	1132	US$/oz
Copper recovery	0.88	-
Gold recovery	0.60	-
Selling cost	0.60	US$/lb
Processing cost	10	US$/ton
Reference mining cost	1.8	US$/ton
Increment mining cost	0.002	US$/ton • m
Slope angle	45	degrees
Time horizon	7	Years
Discount rate	0.10	-
Mining capacity	60 000 000	t/a
Processing capacity	20 000 000	t/a
Minimum exposed ore (as metal)	100 000	t/a

Copper and gold are the two metals of importance in this deposit, and each block has its own set of characteristics, such as tonnage and grade. Moreover, parameters for the given case study such as commodity price, recovery, mining capacity and processing capacity, are shown above.

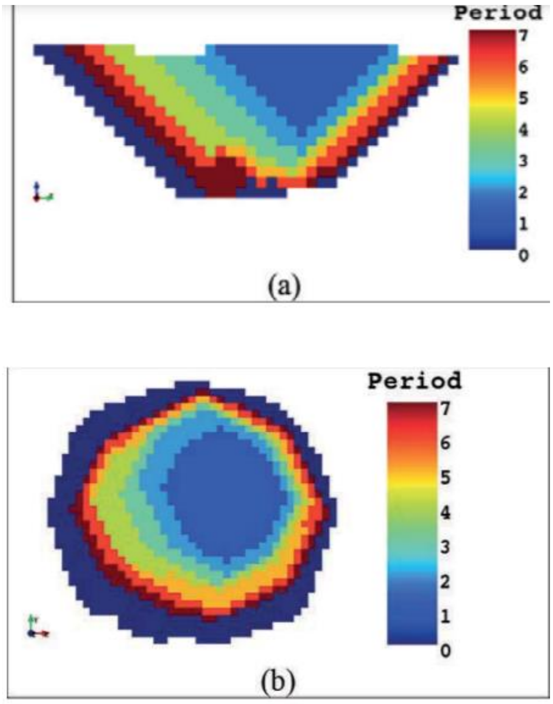

Figure 6. Block Schedules for a 7-year period (Saavedra-Rosas, 2016).

Figure 6 above shows the pits created while scheduling the Marvin example, with a YZ-section view and a horizontal plane for a schedule derived via open pit block sequencing (OPBS). The colors represent the different times when the blocks are removed.

Table 3. Production plans for each period (Saavedra-Rosas, 2016).

Comparison of production plans for the Marvin case study				
Period	OPBS			
	Grade %	Ore tons	Total tons	Exposed tons
1	1.03	19 994 670	59 989 965	0
2	1.14	19 971 010	49 490 568	359
3	1.05	19 980 880	40 052 602	1 462
4	1.02	19 985 340	44 985 249	4 719
5	0.97	19 999 920	49 166 274	7 569
6	0.92	19 999 290	52 191 380	6 254
7	0.88	15 535 850	46 060 989	-
Total		135 466 960	341 937 027	20 363

Production plans for the case study is demonstrated above in Table 3. Grade, ore, and waste tons are determined for each period of time. In terms of applicability, the presented model has a lot of promise, but more algorithmic research is needed to enhance the computational execution time in the case of very large instances (Saavedra-Rosas, 2016). However, it's important to note that the focus of this case study was on introducing the concept and providing the accompanying model.

2.3.3 Case study 3

The case study was produced using a block model of a real iron ore mine in Brazil. This model consists of 38 172 regular blocks of 50 m 50 m 20 m in size (P. Campos et al., 2018). Along with its three-dimensional coordinates, each block includes the following important attributes: tonnage, iron grade, waste, and possible destination (processing plant or waste dump). Economic parameters such as iron price, iron recovery, selling cost, processing cost, and mining cost are considered for economic analysis.

Table 4. The strategic planning of the whole project produced the life-of-mine production plan (P. Campos et al., 2018).

Economic and technical parameters

Parameter	Value	Unit
Iron price	70	US$/t
Iron recovery	0.9	-
Selling cost	18	US$/t
Processing cost	9.45	US$/t
Mining cost	4.5	US$/t
Discount rate	0.1	-
Mining capacity	55	Mt/a
Processing capacity	36.5	Mt/a
	Bearing	**Slope**
Slope angle	0–120° 120–240° 240–360°	45° 35° 30°

In the following case study, three approaches of block sequencing were performed. The first one is a conventional method of scheduling using a renowned software package in the mineral industry (Deswik). The objective was to calculate the tonnage of ore and waste and Net Present Value (NPV) of the first five years. Based on the results, the mass extracted in the first five years (about 281 Mt) was assumed to be medium-term sequenced in the software program. These blocks are outlined in red in Figure 7, while the blocks belonging to the final pit are represented in green and the other blocks in blue.

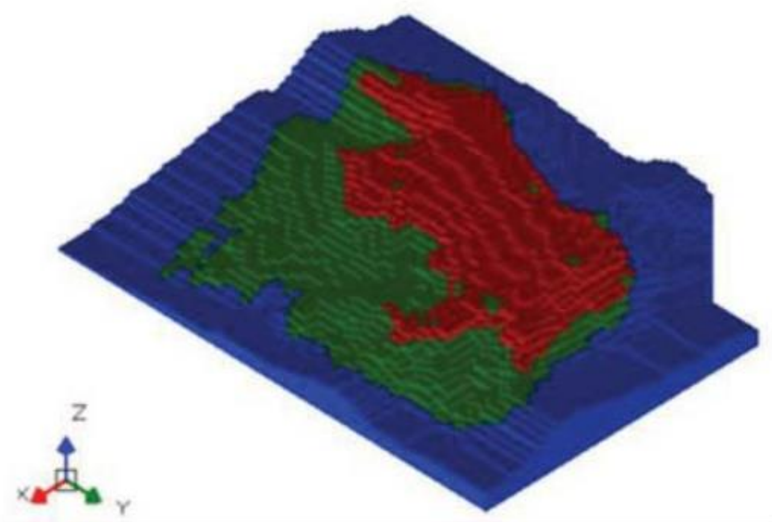

Figure 7. A 3D view of the block model (P. Campos et al., 2018).

Then, the red blocks were rescheduled using the Deswik software to create an annual plan that corresponds to previously set intermediate plan. Figure 8 illustrates this schedule in which the pink blocks indicate the blocks to be removed during that particular period and the green blocks refers to the block to be removed at another period.

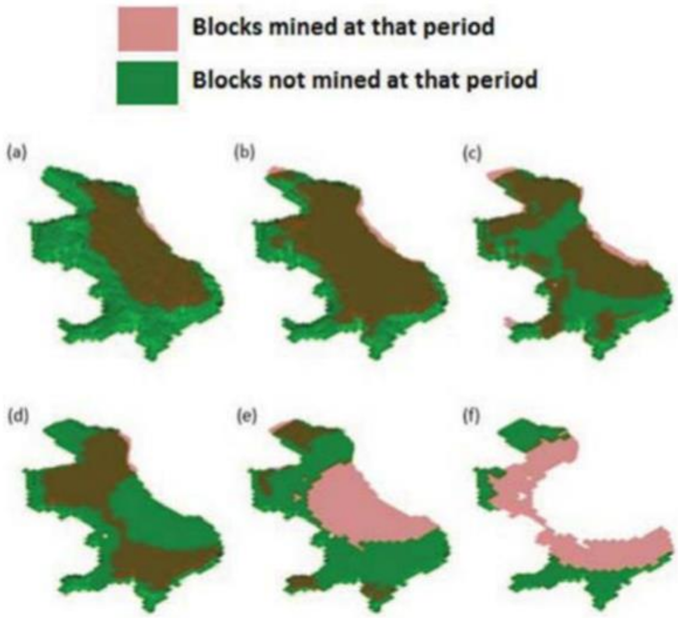

Figure 8. Annual scheduling for the red blocks (P. Campos et al., 2018).

The second approach was completed by using direct block sequencing. To appropriately run the sequencing, the operational and physical constraints such as the horizontal and vertical rates of advance, the minimum mining width, and the maximum number of mining fronts, as well as resource characteristics such as the mining rate, utilization, and availability should be implemented. The results of the case study suggest that the DBS defers overburden removal and attempts to reduce the undiscounted value over time while raising the stripping ratio. Due to the limitation of mining all blocks, the last phase generates more waste and has a negative economic value, lowering the cumulative NPV. Scheduling through DBS plan results in a 10.57% in NPV as compared to conventional scheduling. However, this strategy has unfeasible scheduling results, and there is no way to determine if the blocks have any real benefit. However, combination of the sequencing methods improves the NPV by 0.43 percent; this gain is practical and achievable.

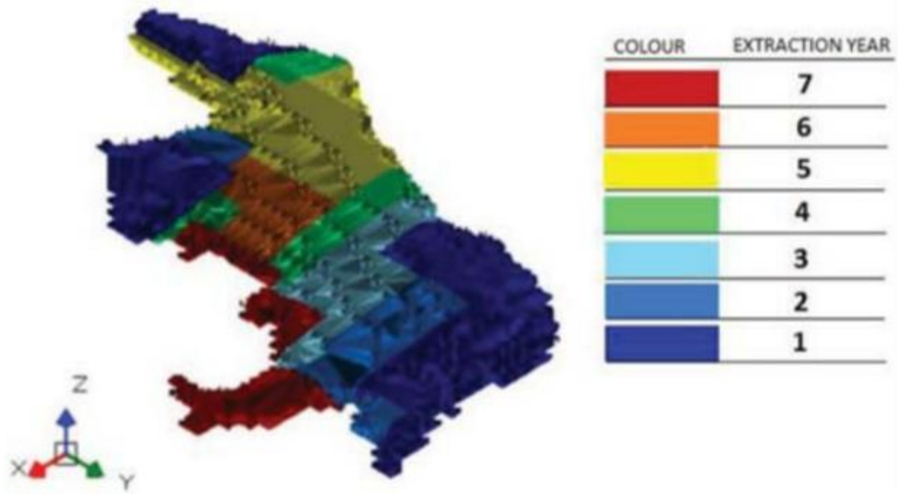

Figure 9. Block sequencing by using Direct Block Sequencing (DBS) (P. Campos et al., 2018).

3. METHODOLOGY

The following research part demonstrates the approaches to analyze mining block sequences and scheduling. The first part defines the mathematical model - linear programming of the block sequencing optimization. This mathematical model is considered as a root function for sequencing and scheduling processes in the mining software. In the second part, mine block sequencing and scheduling simulations were run using Datamine Studio NPVS software.

3.1 Justification of selected methods

Generally, there is no mathematical technique capable of discovering the optimal solution to the block sequencing problem. However, algorithms are available that provide useful alternatives, provided many parameters has been implicitly or explicitly determined under the supervision of a mining planner and depending on the amount and quality of the model's input parameters. We begin by addressing the issue of obtaining the optimal final pit limit for a mine using a collection of all feasible net values and the set of blocks that must initially be extracted, in accordance with the pit slopes, to expose the block under consideration. The ultimate pit is defined as the contour formed by extracting a volume of material with a total maximum net value that also meets the pit slope criteria. While the floating cone approach was a common method for creating the final shape, it did not always provide appropriate results. In research from Bastante et al. (2004), a solution to the issue was discovered in the graph-theoretic approach developed by Lerchs and Grossmann (1965). After defining the phases, we construct the production schedule. While most of the software packages use heuristic search approaches to determine the optimal temporal extraction sequence, some utilize linear programming techniques or a mix of the two.

3.2 Numerical Model

As it was mentioned before, linear programming is the study of solving mathematical optimization problems in which at least some of the decision variables must have integer values. Mathematical models involving integer decision variables are used in a wide variety of applications, most notably when yes/no judgments are required. It is crucially important to understand the working principles (mathematical model) of the common modern software. The long-term scheduling problem for open pit mining is concerned with accurately picking the blocks to mine to optimize the process's total profit over a certain time period. According to Kumral (2012), the conventional mine production planning is formulated as follows (objective function):

$$Max\ f(x) = \sum_{i=1}^{T} \sum_{j=1}^{N} V_{ij}(m) x_{ij} \tag{3}$$

$$\mathrm{m} = \begin{cases} 1\ if\ the\ grade\ of\ block\ j \geq cut-off_i \\ 0\ otherwise \end{cases} \tag{4}$$

$$V_{ij}(1) = (price \times recovery\ \times\ ore\ tonnage\ of\ block\ j\ \times\ grade\ of\ block\ j) - (mining\ cost + processing\ cost \times tonnage\ of\ block\ j) \times (1+n)^{-i} \tag{5}$$

$$V_{ij}(0) = -(mining\ cost \times tonnage\ of\ block\ j) \times (1+n)^{-i} \quad (6)$$

Decision Variable:

$$x_{ij} = \begin{cases} 1\ if\ the\ block\ j\ is\ produced\ in\ period\ i \\ 0\ otherwise \end{cases} \quad (7)$$

Where N is the number of blocks, T is the number of periods, V_{ij} (m) is the present value of block j in period i for classification m, x_{ij} is a binary variable, n is discount rate.

Besides the objective function, it is also important to subject it to the specific constraints Typically, the constraints related to block accessibility, mining and milling capabilities, mill feed and concentrate grades, extraction equipment capacities, and physical and operating requirements such as the minimum width necessary for machinery. Osanloo et al., (2008) provides constraints functions for related areas:

$$G_{min}^{tm} \le \sum_{i=1}^{N} g_i \times TB_i \times x_i^{tm} \,/\, \sum_{i=1}^{N} TB_i \times x_i^{tm} \le G_{max}^{tm}, for\ t\ =\ 1,2,...T\ and\ m = 2,3,...,M \quad (8)$$

$$PC_{min}^{tm} \le \sum_{i=1}^{N} TB_i \times x_i^{tm} \le PC_{max}^{tm}, for\ t\ =\ 1,2,...T\ and\ m = 2,3,...,M \quad (9)$$

$$MC_{min}^{t} \le \sum_{i=1}^{T} \sum_{j=1}^{N} TB_i \times x_i^{tm} \le MC_{max}^{t}, for\ t\ =\ 1,2,...T \quad (10)$$

where T is the maximum number of scheduling periods, N is the total number of blocks to be scheduled, i is the block index, $x_i^{tm}$is the proportion of block i to be mined in period t as a processing type m, g_i is the average grade of block i, TB_i is the total tonnes of material in block i. $G_{min}^{tm}/G_{max}^{tm}$ is the minimum/maximum average grade of the material m sent to the mill in period t, $PC_{min}^{tm}/PC_{max}^{tm}$ is the minimum/maximum processing capacity of material type m in any period, $MC_{min}^{t}/MC_{max}^{t}$ is minimum/maximum mining capacity in any period.

3.3 Software computation

To run software simulation of sequencing, geological block model referred to real-world gold-copper deposit is considered as a main input of the software (Madani, 2021). The mining areas were defined using the lithological units and geotechnical features of the rock. To begin, Datamine Studio NPVS was used to do a preliminary pit optimization to evaluate the possible placement of the ultimate pit limit. The block model is already produced for both Copper and Gold in Datamine Studio RM. However before running the software simulation, firstly the economic parameters of base case, optimistic and pessimistic should be set to derive economic block model. Annual discount rate is set to 10%. Tables 5, 6 and 7 illustrate the economic parameters of project scenario.

Table 5. Economic parameters of base case (Madani, 2021).

Rock type	Element	Price	Selling cost		Mining cost ($/t)	Processing cost ($/t)
Ore	**Gold (/g)**	**$ 41.80**	**2.5%**	**$ 1.05**	**$ 5.00**	**$ 36.91**
	Copper (/t)	**$ 6,410.00**	**2.5%**	**$ 160.25**		
Soil	-	-	-	-	$ 3	-
Weathered rock	-	-	-	-	$ 4	-
Fresh rock	-	-	-	-	$ 4.75	-

Table 6. Economic parameters of optimistic scenario (Madani, 2021).

Rock type	Element	Price	Selling cost		Mining cost ($/t)	Processing cost ($/t)
Ore	**Gold (/g)**	**$ 50.16**	**2.5%**	**$ 1.25**	**$ 4.00**	**$ 29.53**
	Copper (/t)	**$ 7,692.00**	**2.5%**	**$ 192.30**		
Soil	-	-	-	-	$ 2.40	-
Weathered rock	-	-	-	-	$ 3.20	-
Fresh rock	-	-	-	-	$ 3.80	-

Table 7. Economic parameters of pessimistic scenario (Madani, 2021).

Rock type	Element	Price	Selling cost		Mining cost ($/t)	Processing cost ($/t)
Ore	**Gold (/g)**	**$ 33.44**	**2.5%**	**$ 0.84**	**$ 6.00**	**$ 44.29**
	Copper (/t)	**$ 5,128.00**	**2.5%**	**$ 128.20**		
Soil	-	-	-	-	$ 3.60	-
Weathered rock	-	-	-	-	$ 4.80	-
Fresh rock	-	-	-	-	$ 3.80	-

The second step in software simulation is to adjust geotechnical and other technical restriction parameters. In this section, the recovery information was adjusted as well.

Table 8. Recovery formulas (Madani, 2021).

Element	Recovery formulas
Gold	If (Au<1,0,(0.0207*(Au**3)-1.3576*(Au**2)+22.58*(Au)-17.204)/100)
Copper	If (Cu<0.1,0,(1713*(Cu**3)-2236*(Cu**2)+987.83*(Cu)-76.667)/100)

The formulas identifies that the recovery of grade less than 1 g/t is equal to zero. However, grades above 1 g/t are recovered by the above formula. Specifically, higher grade blocks could be recovered better, while the low-grade blocks' recovery is slightly less than the higher ones. The same is for copper, the recovery for grades less than 0.1% is equivalent to 0.

While the higher grades are recovered by the given formula. Figures 10 and 11 shows graphical interpretations of recovery with respect to the grade.

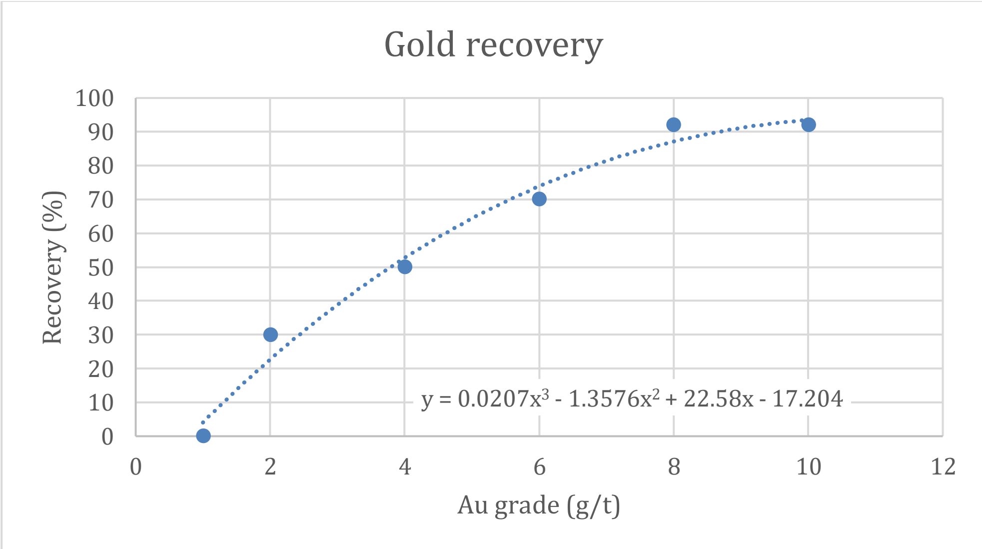

Figure 10. The graph of Au recovery.

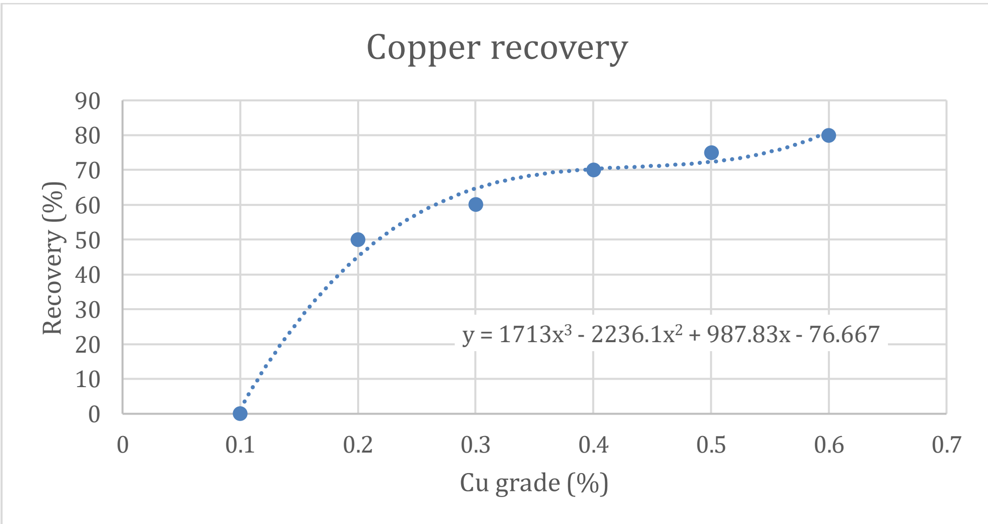

Figure 11. The graph of Cu recovery.

To obtain an ultimate pit limit, overall slope angles were adjusted for the different rock types. The following slope angles in Table 7 allow to find the highest possible cashflow within a pit limit. For pushback, mining width should be adjusted properly for pushback generation. The movement of this equipment (shovel truck) at the mine's bottom usually requires a minimum bottom width of 30 meters (Nancel-Penard & Morales, 2021).

Table 9. Geotechnical information of block model (Madani, 2021).

Material	Overall angle (°)
Soil	25
Fresh rock	55
Weathered rock	45
Ore	55
Mining width	**30 m**

4. RESULTS

4.1 Base Scenario

The main outputs of gold-copper open pit mine software simulation are production scheduling, economic cut-off grade, life of mine, generated Lerchs-Grossman phases, extraction sequence, pushbacks and finally, economic output of the project. Figures 13 - 16 demonstrate the mining pushbacks of the project. The software provided four pushbacks for the entire time horizon of the project.

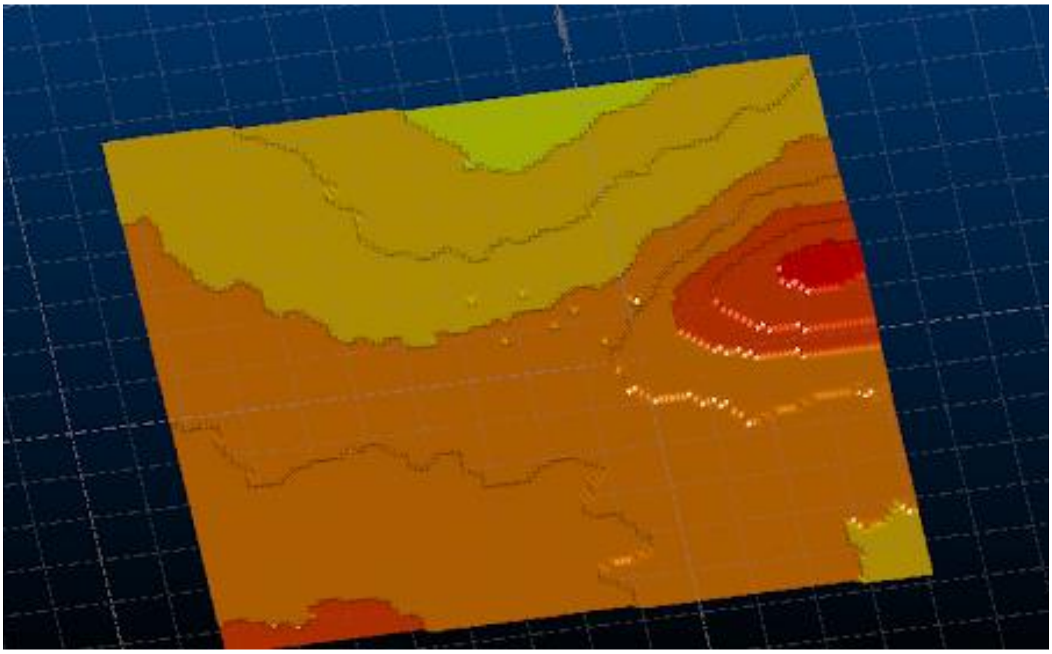

Figure 12. Side view before mining operations.

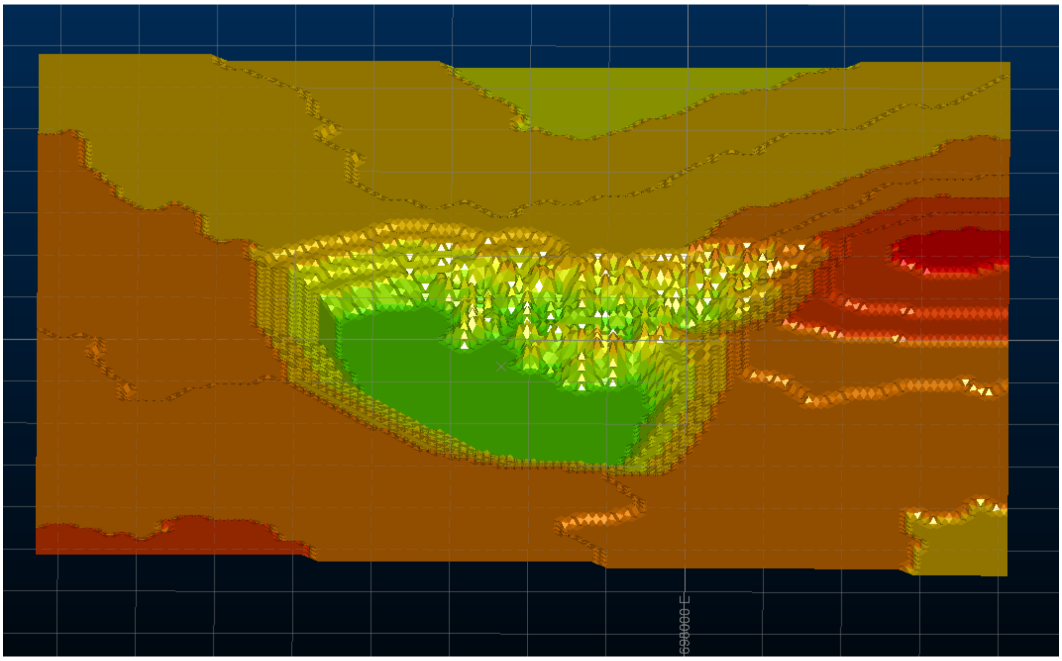

Figure 13. Side view of pushback no. 1 (Base Case).

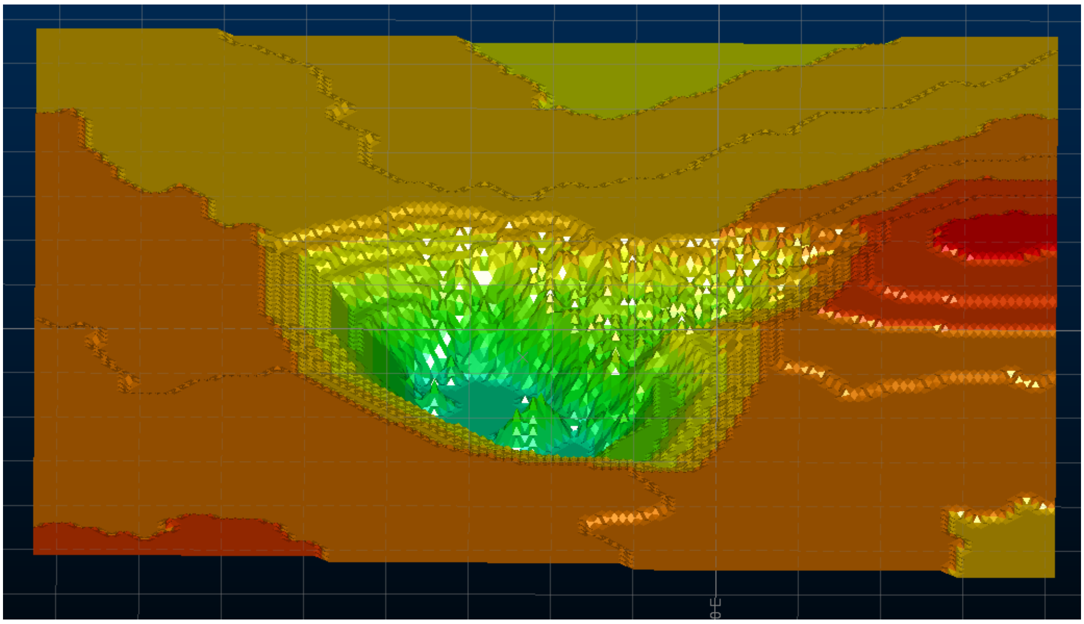

Figure 14. Side view of pushback no. 2 (Base Case).

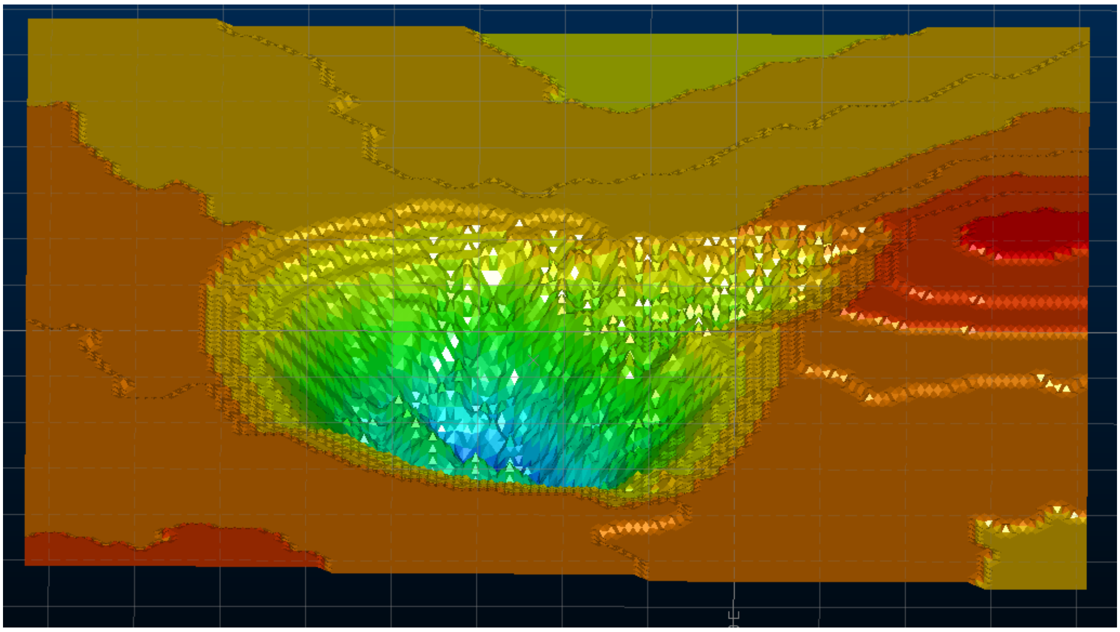

Figure 15. Side view of pushback no. 3 (Base Case).

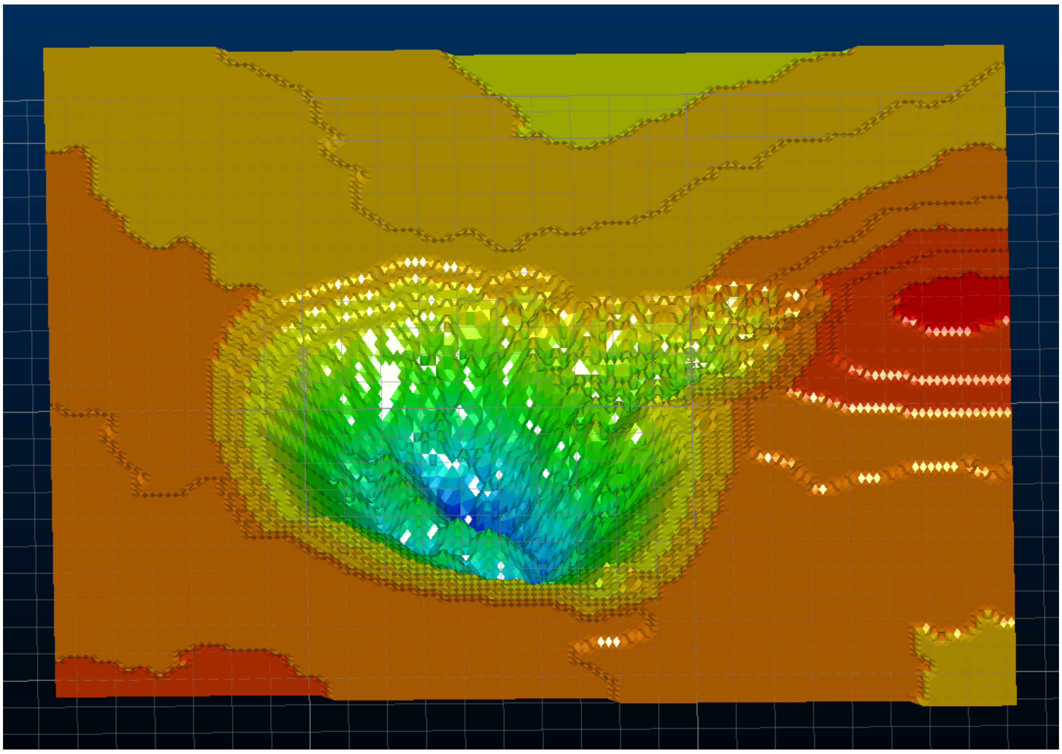

Figure 16. Side view of pushback 4 (Base Case).

Moreover, tonnage of ore and waste are demonstrated in Table 8 below.

Table 10. Ore, waste, and profit generated within each pushback (Base Case).

Pushbacks			
Pushback	ORE	Waste	Profit
1	4,812,600	26,607,700	586,657,659
2	5,967,000	10,640,000	820,172,602
3	3,268,200	27,310,600	352,432,072
4	3,564,600	19,224,000	446,528,618

After determining the pushback designs, the final pit limit could be obtained through the software. The results of the pit limit are shown in Figures 17 and 18.

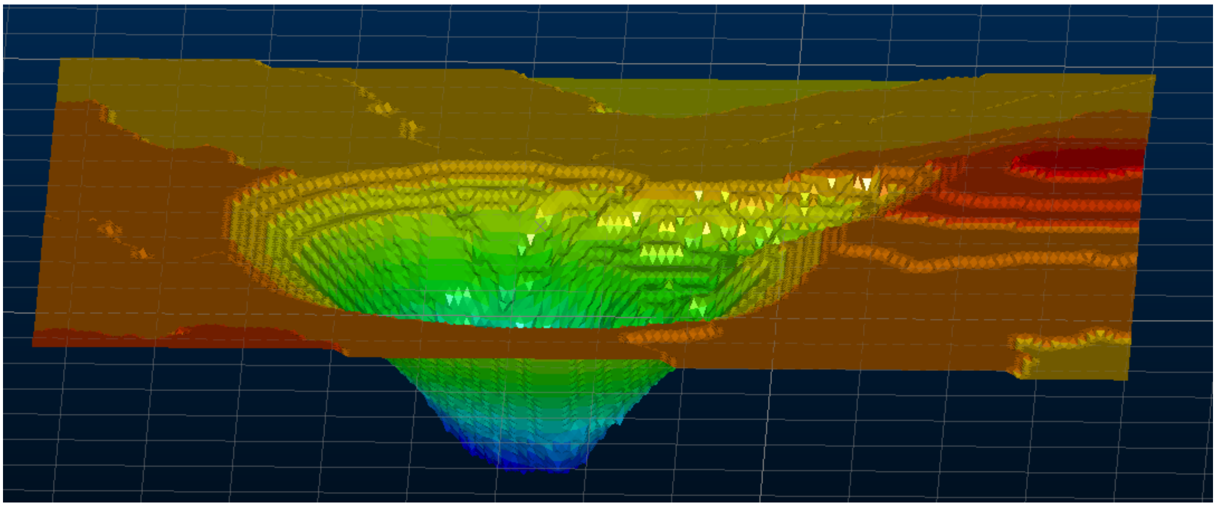

Figure 17. Side view of the pit limit (Base Case).

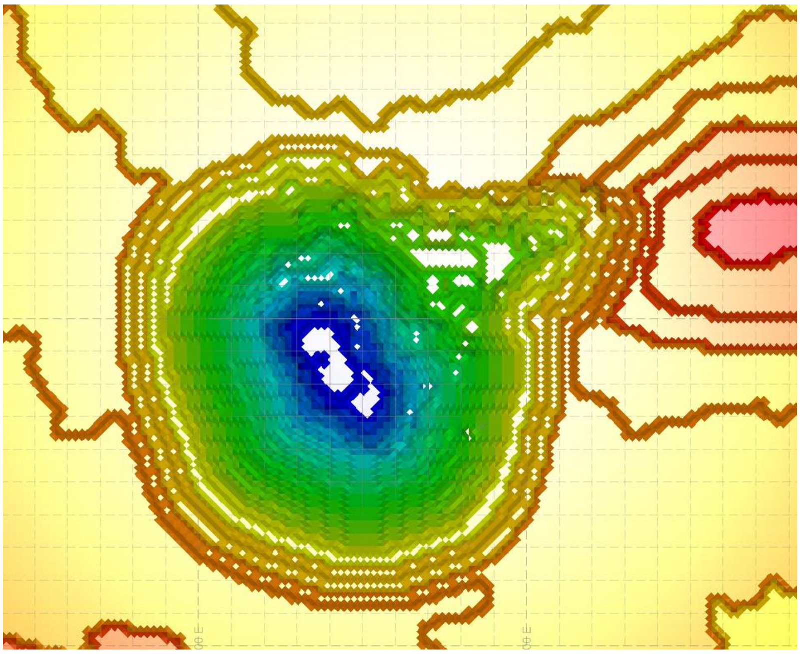

Figure 18. Plan view of pit limit (Base Case).

The lifetime of the project is predicted to be 10 years in accordance with the highest net present value of the project. In other words, extracting blocks after 10 years is not economically profitable. Table 11 below shows the results of simulation of 10 years of production – revenue, mining and processing costs for the entire project.

Table 11. Scheduling results of the project (Base Case).

Schedule		
	Lifetime	NPV at per Year discount
	Years	$
	10	610,563,364

To be more precise, those 10 years are then split into one year time horizon (Table 12). Specific values of rock tonnes, revenue, mining, and processing cost, NPV and tonnage of other types of rocks.

Table 12. Scheduling results by time periods (Base Case).

Year	Rock	Revenue	Processing Cost	Mining Cost	Capital Costs	NPV	ORE	ORE (w)	WEATH	SOIL	FRESH	Au	Cu	Au R	Cu R	Strip
	tonnes	$	$	$	$	$	tonnes	tonnes	tonnes	tonnes	tonnes	g	tonnes	g	tonnes	
1	2,533,200	68,886,854	18,569,421	9,768,000	0.0000	38,324,234	503,100	581,100	0.0000	1,449,000	0.0000	2,441,055	948.8666	1,613,540	499.0751	4.0352
2	7,506,600	135,851,071	37,291,293	26,747,400	0.0000	65,107,098	1,002,300	1,111,500	0.0000	5,392,800	0.0000	4,856,194	1,807	3,191,023	925.9921	6.4894
3	12,652,500	212,120,903	56,325,165	44,376,900	0.0000	96,166,545	1,501,500	1,708,200	0.0000	9,442,800	0.0000	7,450,365	2,696	4,993,384	1,375	7.4266
4	26,146,100	503,777,143	136,457,802	98,508,875	0.0000	207,191,195	3,502,200	4,134,000	4,716,800	13,746,600	46,500	17,565,504	6,505	11,841,176	3,383	6.4656
5	35,865,000	785,187,238	222,420,939	141,759,450	0.0000	303,999,831	5,502,900	6,501,300	10,058,400	13,746,600	55,800	27,479,374	10,236	18,446,023	5,335	5.5175
6	43,342,600	1,069,031,443	314,955,576	176,881,600	0.0000	394,108,668	7,503,600	9,679,800	12,313,400	13,746,600	99,200	37,427,936	14,233	25,071,043	7,543	4.7762
7	64,395,200	1,383,437,900	413,984,064	262,097,600	0.0000	463,068,006	9,500,400	12,901,200	23,718,200	18,052,200	223,200	48,043,201	18,032	32,474,353	9,569	5.7782
8	76,555,800	1,700,085,857	520,012,701	313,997,625	0.0000	538,546,474	11,501,100	15,732,600	29,466,800	19,629,000	226,300	58,730,960	21,826	39,934,379	11,583	5.6564
9	83,429,900	2,022,433,162	633,221,238	346,993,775	0.0000	613,698,726	13,501,800	19,227,000	30,839,600	19,629,000	232,500	69,551,495	25,596	47,533,373	13,603	5.1792
10	83,796,500	2,075,547,705	652,338,258	348,826,775	0.0000	626,673,257	13,813,800	19,281,600	30,839,600	19,629,000	232,500	71,311,819	26,115	48,797,372	13,858	5.0661

The following results on nested pits or Lerchs-Grossman phases shows the specific sequence of the mining extraction with respect to time. Each phase has specific ore and waste tonnage, mining, and processing costs, revenue, and Net Present Value. Table 13 illustrates the results of LG phases. The highest cumulative NPV is observed in Pit 88 – 649,027,644 $.

Table 13. LG phases (Base Case).

57	Pit 50 (61)	Pit 50	61.00%	69,865,800	1,893,165,228	573,132,885	292,011,300	0.0000	636,442,278	12,343,500	17,070,300	23,434,400	16,930,800	86,800	64,523,431	23,350	44,549,030	12,384
58	Pit 51 (62)	Pit 51	62.00%	70,002,300	1,898,391,271	575,640,273	292,693,800	0.0000	637,033,052	12,390,300	17,160,000	23,434,400	16,930,800	86,800	64,728,690	23,452	44,668,375	12,441
59	Pit 52 (63)	Pit 52	63.00%	70,056,900	1,900,036,286	576,446,169	292,966,800	0.0000	637,196,823	12,405,900	17,199,000	23,434,400	16,930,800	86,800	64,795,027	23,478	44,706,741	12,454
60	Pit 53 (64)	Pit 53	64.00%	70,088,100	1,901,690,022	577,360,914	293,122,800	0.0000	637,365,200	12,425,400	17,210,700	23,434,400	16,930,800	86,800	64,867,945	23,528	44,743,017	12,482
61	Pit 54 (65)	Pit 54	65.00%	70,258,400	1,906,029,862	579,494,604	293,848,100	0.0000	637,791,567	12,464,400	17,253,600	23,485,000	16,968,600	86,800	65,039,127	23,596	44,843,528	12,521
62	Pit 55 (66)	Pit 55	66.00%	70,285,700	1,907,029,324	580,012,251	293,984,600	0.0000	637,890,764	12,476,100	17,269,200	23,485,000	16,968,600	86,800	65,085,526	23,606	44,867,895	12,522
63	Pit 56 (67)	Pit 56	67.00%	70,348,600	1,910,305,722	581,880,741	294,294,700	0.0000	638,205,300	12,515,100	17,288,700	23,489,400	16,968,600	86,800	65,233,557	23,680	44,942,685	12,559
64	Pit 57 (68)	Pit 57	68.00%	70,677,700	1,916,550,522	584,773,527	295,671,400	0.0000	638,767,490	12,569,700	17,362,800	23,621,400	17,037,000	86,800	65,476,376	23,771	45,089,203	12,602
65	Pit 58 (69)	Pit 58	69.00%	70,826,000	1,918,708,498	585,719,472	296,219,900	0.0000	638,955,940	12,589,200	17,394,000	23,623,600	17,132,400	86,800	65,559,297	23,814	45,138,453	12,626
66	Pit 59 (70)	Pit 59	70.00%	70,880,600	1,920,628,578	586,883,115	296,492,900	0.0000	639,092,913	12,616,500	17,421,300	23,623,600	17,132,400	86,800	65,654,385	23,856	45,182,620	12,646
67	Pit 60 (71)	Pit 60	71.00%	70,943,500	1,923,584,571	588,701,256	296,803,000	0.0000	639,326,779	12,651,600	17,444,700	23,628,000	17,132,400	86,800	65,790,747	23,894	45,253,198	12,658
68	Pit 61 (72)	Pit 61	72.00%	76,763,400	1,991,080,647	613,735,395	320,263,125	0.0000	644,450,674	13,084,500	18,298,800	27,049,000	18,241,200	89,900	68,100,925	24,629	46,852,988	13,025
69	Pit 62 (73)	Pit 62	73.00%	77,194,900	1,998,165,256	616,834,179	322,278,100	0.0000	644,980,193	13,146,900	18,447,000	27,115,000	18,262,800	223,200	68,378,342	24,718	47,019,451	13,073
70	Pit 63 (74)	Pit 63	74.00%	77,904,800	2,004,599,053	618,858,669	324,986,600	0.0000	645,434,399	13,185,900	18,458,700	27,592,400	18,444,600	223,200	68,587,752	24,820	47,168,199	13,132
71	Pit 64 (75)	Pit 64	75.00%	77,928,200	2,005,512,594	619,423,116	325,103,600	0.0000	645,496,429	13,197,600	18,470,400	27,592,400	18,444,600	223,200	68,632,189	24,825	47,190,617	13,132
72	Pit 65 (76)	Pit 65	76.00%	78,393,600	2,010,593,753	621,401,157	326,964,600	0.0000	645,826,701	13,232,700	18,544,500	27,838,800	18,554,400	223,200	68,807,234	24,918	47,306,403	13,190
73	Pit 66 (77)	Pit 66	77.00%	79,900,600	2,025,247,490	626,685,033	332,923,000	0.0000	646,724,197	13,326,300	18,739,500	28,699,000	18,912,600	223,200	69,309,243	25,068	47,655,743	13,257
74	Pit 67 (78)	Pit 67	78.00%	81,028,100	2,037,865,716	632,073,507	337,375,700	0.0000	647,448,300	13,427,700	18,805,800	29,433,800	19,137,600	223,200	69,773,542	25,289	47,945,490	13,386
75	Pit 68 (79)	Pit 68	79.00%	81,112,100	2,039,021,127	632,634,054	337,720,700	0.0000	647,513,443	13,439,400	18,817,500	29,480,000	19,152,000	223,200	69,818,885	25,331	47,969,586	13,413
76	Pit 69 (80)	Pit 69	80.00%	81,141,700	2,040,531,688	633,689,199	337,867,150	0.0000	647,593,918	13,458,900	18,821,400	29,480,000	19,152,000	229,400	69,891,708	25,353	48,005,615	13,420
77	Pit 70 (81)	Pit 70	81.00%	81,221,400	2,042,094,416	634,623,444	338,191,650	0.0000	647,672,897	13,478,400	18,829,200	29,510,800	19,173,600	229,400	69,962,164	25,399	48,040,059	13,446
78	Pit 71 (82)	Pit 71	82.00%	83,103,400	2,058,695,589	640,631,667	345,671,650	0.0000	648,467,218	13,583,700	19,035,900	30,720,800	19,533,600	229,400	70,520,370	25,610	48,428,805	13,566
79	Pit 72 (83)	Pit 72	83.00%	83,201,200	2,060,978,837	642,080,010	346,140,850	0.0000	648,560,994	13,611,000	19,086,600	30,740,600	19,533,600	229,400	70,624,350	25,651	48,481,757	13,586
80	Pit 73 (84)	Pit 73	84.00%	83,228,500	2,062,075,601	642,862,155	346,277,350	0.0000	648,606,600	13,630,500	19,094,400	30,740,600	19,533,600	229,400	70,681,131	25,707	48,503,203	13,622
81	Pit 74 (85)	Pit 74	85.00%	83,232,400	2,062,295,625	643,029,504	346,296,850	0.0000	648,615,085	13,634,400	19,094,400	30,740,600	19,533,600	229,400	70,690,746	25,728	48,506,138	13,638
82	Pit 75 (86)	Pit 75	86.00%	83,372,200	2,063,998,451	643,964,100	346,846,450	0.0000	648,670,913	13,650,000	19,094,400	30,839,600	19,558,800	229,400	70,760,002	25,743	48,547,716	13,639
83	Pit 76 (87)	Pit 76	87.00%	83,426,800	2,065,840,990	645,284,094	347,119,450	0.0000	648,734,528	13,673,400	19,125,600	30,839,600	19,558,800	229,400	70,845,473	25,785	48,589,214	13,663
84	Pit 77 (88)	Pit 77	88.00%	83,446,300	2,066,664,770	645,907,041	347,216,950	0.0000	648,760,828	13,685,100	19,133,400	30,839,600	19,558,800	229,400	70,885,806	25,806	48,607,632	13,675
85	Pit 78 (89)	Pit 78	89.00%	83,543,000	2,068,826,355	647,335,884	347,699,675	0.0000	648,824,276	13,712,400	19,199,700	30,839,600	19,558,800	232,500	70,978,477	25,898	48,650,918	13,738
86	Pit 79 (90)	Pit 79	90.00%	83,605,400	2,071,191,767	649,150,125	348,011,675	0.0000	648,884,823	13,747,500	19,227,000	30,839,600	19,558,800	232,500	71,089,942	26,004	48,698,312	13,807
87	Pit 80 (91)	Pit 80	91.00%	83,617,100	2,071,691,323	649,543,323	348,070,175	0.0000	648,896,917	13,755,300	19,230,900	30,839,600	19,558,800	232,500	71,115,699	26,018	48,709,536	13,814
88	Pit 81 (92)	Pit 81	92.00%	83,671,700	2,073,323,939	650,761,917	348,343,175	0.0000	648,932,490	13,778,700	19,262,100	30,839,600	19,558,800	232,500	71,194,764	26,071	48,745,262	13,842
89	Pit 82 (93)	Pit 82	93.00%	83,788,700	2,075,181,795	652,034,760	348,787,775	0.0000	648,967,806	13,806,000	19,281,600	30,839,600	19,629,000	232,500	71,289,331	26,103	48,789,024	13,854
90	Pit 83 (94)	Pit 83	94.00%	83,796,500	2,075,547,705	652,338,258	348,826,775	0.0000	648,973,689	13,813,800	19,281,600	30,839,600	19,629,000	232,500	71,311,819	26,115	48,797,372	13,858
91	Pit 84 (95)	Pit 84	95.00%	83,804,300	2,076,004,328	652,731,456	348,865,775	0.0000	648,979,822	13,821,600	19,281,600	30,839,600	19,629,000	232,500	71,335,663	26,135	48,806,852	13,869
92	Pit 85 (96)	Pit 85	96.00%	83,852,100	2,077,741,370	654,163,848	349,100,400	0.0000	648,997,354	13,852,800	19,293,300	30,839,600	19,630,800	235,600	71,429,618	26,200	48,844,285	13,903
93	Pit 86 (97)	Pit 86	97.00%	83,906,100	2,079,448,172	655,553,691	349,356,000	0.0000	649,012,674	13,880,100	19,312,800	30,839,600	19,638,000	235,600	71,515,650	26,262	48,880,379	13,941
94	Pit 87 (98)	Pit 87	98.00%	83,929,500	2,080,362,750	656,328,387	349,473,000	0.0000	649,018,375	13,895,700	19,320,600	30,839,600	19,638,000	235,600	71,563,796	26,295	48,900,022	13,959
95	Pit 88 (99)	Pit 88	99.00%	84,134,900	2,082,770,147	657,784,179	350,386,400	0.0000	649,027,644	13,926,900	19,383,000	30,949,600	19,639,800	235,600	71,679,261	26,318	48,958,487	13,963
96	Pit 89 (User)	0	0	87,772,900	2,088,159,808	662,444,055	366,614,425	0.0000	645,193,730	14,020,500	21,352,500	32,045,200	20,066,400	288,300	71,972,173	26,467	49,080,417	14,030

Going on to economic results, the software calculated an economical cut-off grade for the project. In other words, a specific cut-off grade for economic viability of the project. Since input data included two elements – gold and copper, it provided two distinct economic cut-off grades for the project. Table 14 presents the results of the economic cut-off grade (COG).

Table 14. The cut-off grades of the base case.

Au Economic COG	2.6743	g/tonne
Cu Economic COG	0.6481%	Percent

Finally, economic results on the entire project are shown in Table 15 and in Figure 20 below. Moreover, block count and total mass of ore and waste are provided as well. As earlier mentioned, the trend of NPV (red line) is supposed to decrease within Pit no. 89.

Table 15. Economic output of the simulation (Base Case).

Global Stats														
Cash	Revenue	Minimum	Maximum	Process Cost	Minimum	Maximum	Mining Cost	Minimum	Maximum	Net Value	Ore Value			
	2,316,226,171	144,736	1,556,381	752,843,871	143,949	245,349	4,700,398,025	5,400	19,500	(3,137,015,725)	1,485,791,800			
	Block Count	Mass												
ORE	3,979	15,518,100												
Waste	409,605	1,062,434,900												
Total	413,584	1,077,953,000												
Strip Ratio	68.4642													
ORE Stats														
	Mass	Au	Au Min	Au Max	Cu	Cu Min	Cu Max	Au R	Au R Min	Au R Max	Cu R	Cu R Min	Cu R Max	
	tonnes	g	g/tonne	g/tonne	tonnes	Percent	Percent	g	g/tonne	g/tonne	tonnes	Percent	Percent	
ORE	15,518,100	79,794,620	1.8980	9.9856	29,290	0.0003%	0.5994%	54,449,945	0.3968	9.3377	15,504	0.0001%	0.4855%	
Waste Stats														
ORE (w)	28,446,600													
WEATH	355,102,000													
SOIL	94,024,800													
FRESH	584,861,500													
Total	1,062,434,900													

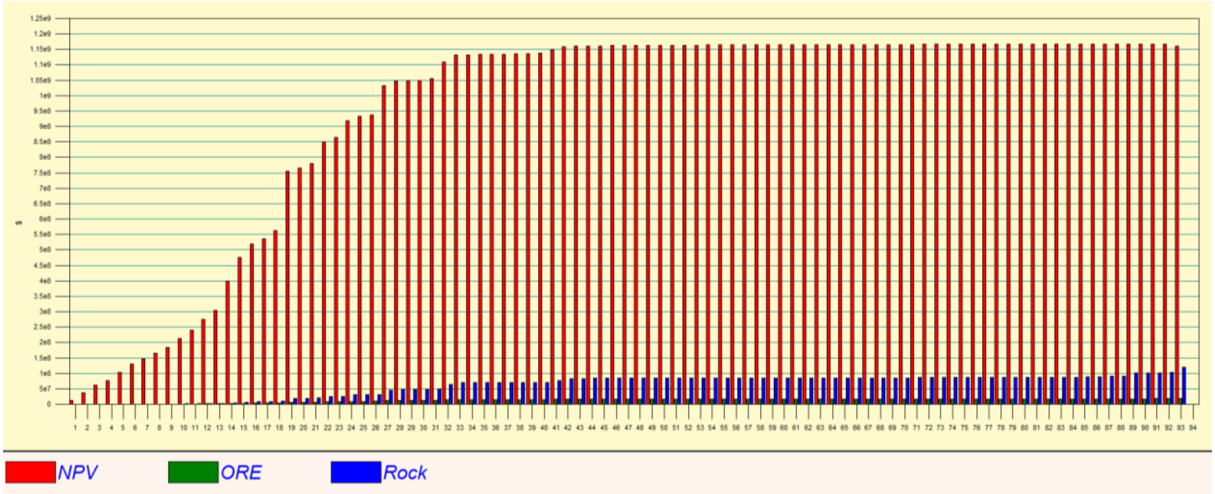

Figure 19. The histogram of NPV, ore and waste tonnage (Base Case).

4.2 Optimistic Scenario

Figures 20 - 22 demonstrate the mining pushbacks of the project. The software provided three pushbacks for the optimistic scenario.

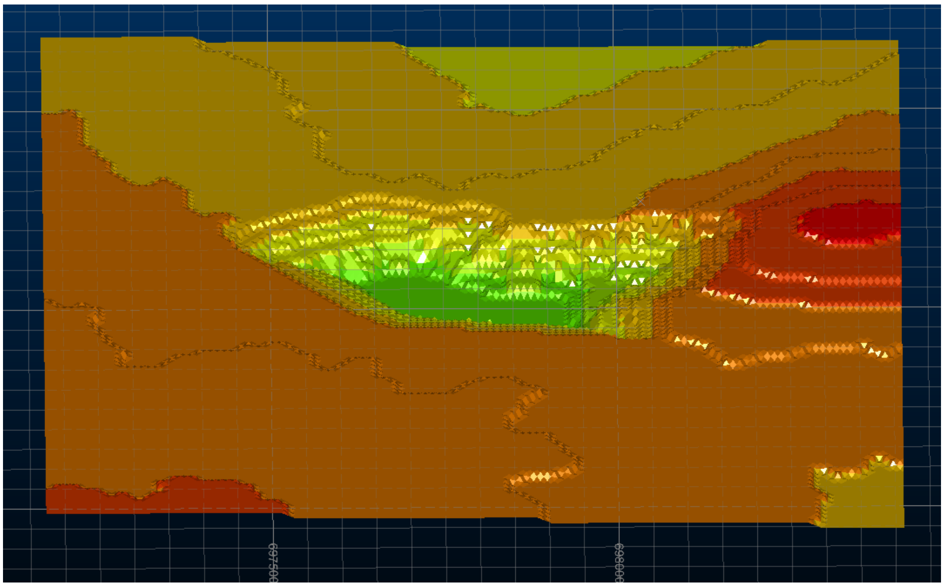

Figure 20. Side view of pushback no. 1 (Optimistic Scenario).

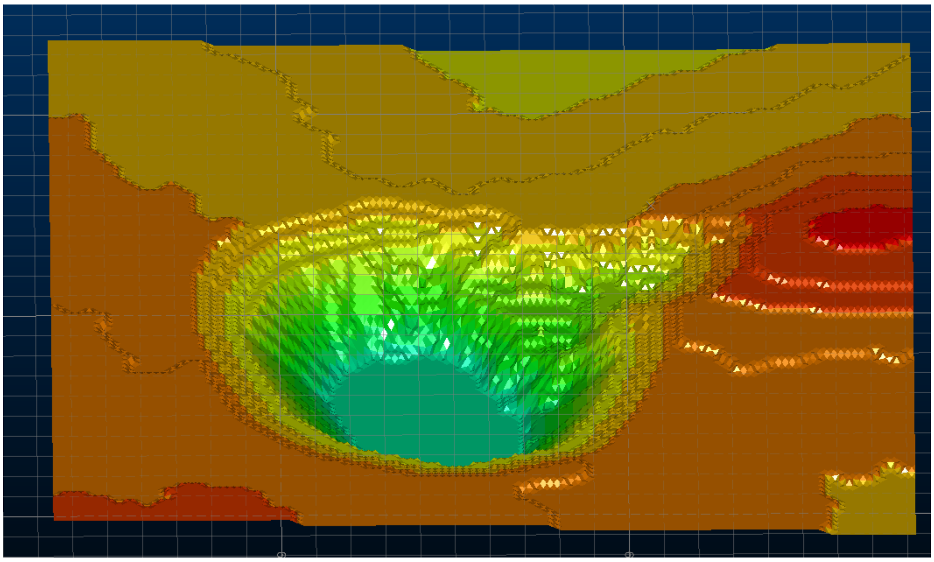

Figure 21. Side view of pushback no. 2 (Optimistic Scenario).

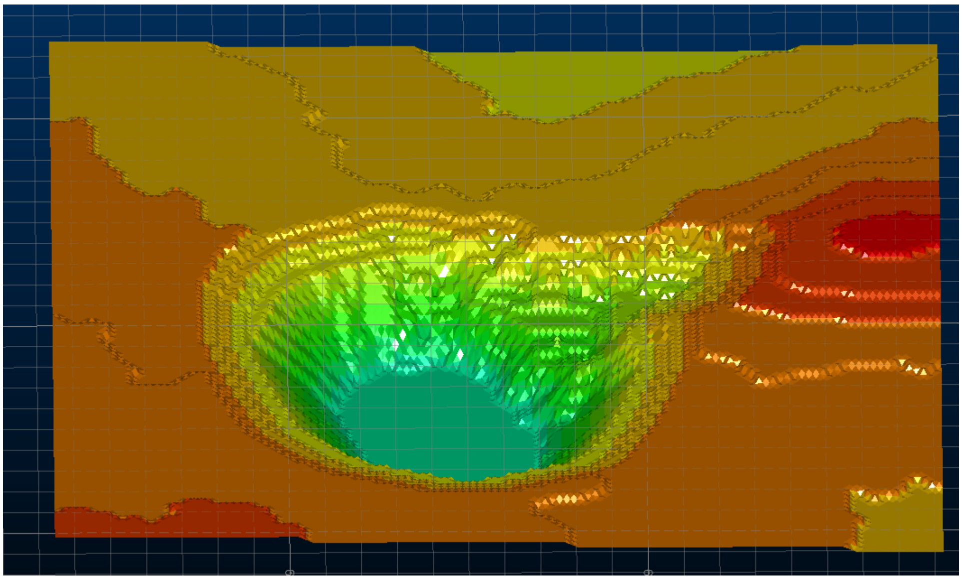

Figure 22. Side view of pushback no. 3 (Optimistic Scenario).

Table 16 provides the tonnage ore, waste and profit for each pushback.

Table 16. Ore, waste, and profit generated within each pushback (Optimistic Scenario).

Pushbacks			
Pushback	ORE	Waste	Profit
1	5,319,600	14,675,500	454,349,329
2	4,995,900	49,569,800	286,557,261
3	3,357,900	7,235,500	292,755,297

Then, the final shape for ultimate pit limit is constructed. The figures below demonstrate the graphical illustrations of the ultimate pit limit of the optimistic scenario.

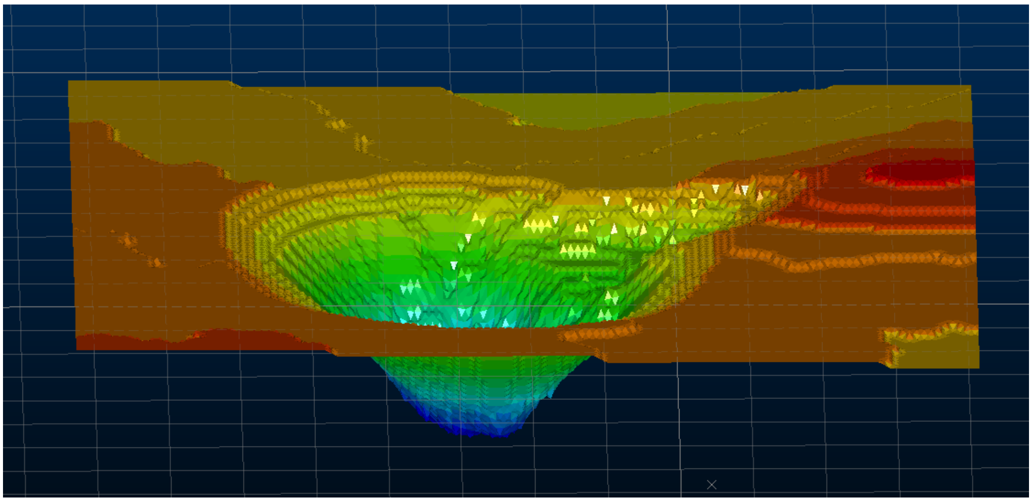

Figure 23. Side view of pit limit (Optimistic Scenario).

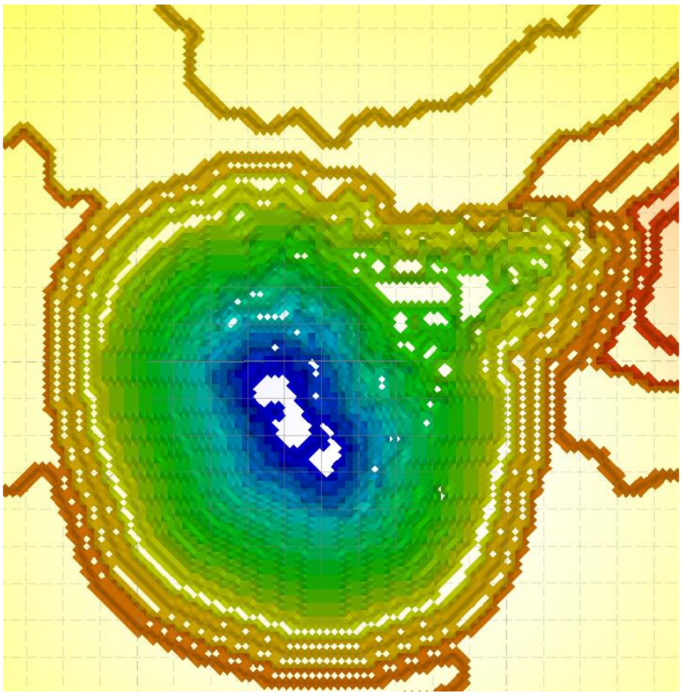

Figure 24. Plan view of pit limit (Optimistic Scenario).

The lifetime of the project is also predicted to be 10 years. Table 17 below shows the results of simulation of 10 years of production – revenue, mining and processing costs for the entire project.

Table 17. Scheduling results by time periods

Cumulative Data																
Year	Rock	Revenue	Processing Cost	Mining Cost	Capital Costs	NPV	ORE	ORE (w)	WEATH	SOIL	FRESH	Au	Cu	Au R	Cu R	Strip
	tonnes	$	$	$	$	$	tonnes	tonnes	tonnes	tonnes	tonnes	g	tonnes	g	tonnes	
1	2,005,800	85,805,285	17,390,217	6,548,640	0.0000	58,133,138	588,900	495,300	0.0000	921,600	0.0000	2,624,424	1,140	1,660,846	609.7970	2.4060
2	4,755,000	168,673,255	34,547,799	14,881,440	0.0000	106,434,465	1,158,300	1,010,100	0.0000	2,586,600	0.0000	5,167,839	2,216	3,268,030	1,178	3.1052
3	7,865,700	265,045,073	52,612,716	24,113,040	0.0000	158,575,777	1,747,200	1,524,900	0.0000	4,593,600	0.0000	7,987,975	3,288	5,155,615	1,718	3.5019
4	15,389,500	618,396,915	127,029,045	50,119,760	0.0000	333,958,049	4,036,500	3,728,400	864,600	6,710,400	49,600	18,628,672	7,559	12,037,743	3,951	2.8126
5	46,981,500	967,337,910	208,254,774	144,492,360	0.0000	443,132,265	6,325,800	5,986,500	14,927,000	19,674,000	68,200	29,149,325	12,116	18,793,154	6,422	6.4270
6	61,673,100	1,325,576,683	299,958,477	195,924,540	0.0000	560,940,525	8,700,900	9,114,300	24,087,800	19,674,000	96,100	40,066,689	16,604	25,748,075	8,832	6.0881
7	71,289,500	1,713,369,444	396,917,508	230,980,960	0.0000	685,754,751	11,013,600	12,070,500	28,320,600	19,674,000	210,800	51,397,757	21,085	33,306,634	11,246	5.4729
8	78,765,600	2,109,326,493	504,334,077	259,235,340	0.0000	798,668,547	13,380,900	15,093,000	30,371,000	19,675,800	244,900	62,992,433	25,742	41,016,903	13,759	4.8864
9	84,799,300	2,508,133,039	620,991,111	282,991,640	0.0000	898,201,281	15,728,700	18,298,800	30,841,800	19,675,800	254,200	74,648,318	30,090	48,813,777	16,087	4.3914
10	85,154,200	2,542,151,740	630,803,160	284,411,240	0.0000	906,453,435	15,912,000	18,470,400	30,841,800	19,675,800	254,200	75,622,696	30,384	49,488,135	16,226	4.3516

Table 18 below shows LG phases of the optimistic scenario. The highest cumulative NPV is observed in Pit 88 – 914,612,423 $.

Table 18. LG phases (Optimistic Scenario).

Pit 41 (52)	Pit 41	52.00%	48,000,800	1,903,126,334	425,364,810	161,666,260	0.0000	821,017,258	11,427,000	11,399,700	12,291,400	12,805,200	77,500	55,636,254	21,958	37,112,191	11,730
Pit 42 (53)	Pit 42	53.00%	48,260,400	1,916,384,883	430,036,386	162,702,900	0.0000	823,409,538	11,536,200	11,547,900	12,293,600	12,805,200	77,500	56,081,933	22,181	37,363,558	11,858
Pit 43 (54)	Pit 43	54.00%	48,392,800	1,923,708,725	432,715,725	163,228,880	0.0000	824,703,284	11,602,500	11,602,500	12,295,800	12,805,200	86,800	56,343,929	22,287	37,506,180	11,905
Pit 44 (55)	Pit 44	55.00%	48,466,900	1,928,219,920	434,272,995	163,503,680	0.0000	825,540,975	11,641,500	11,614,200	12,315,600	12,808,800	86,800	56,499,423	22,373	37,591,157	11,952
Pit 45 (56)	Pit 45	56.00%	49,163,000	1,941,259,182	437,278,335	165,655,120	0.0000	827,987,678	11,719,500	11,680,500	12,628,000	13,048,200	86,800	56,886,721	22,512	37,848,281	12,014
Pit 46 (57)	Pit 46	57.00%	49,527,900	1,948,735,201	439,040,472	166,790,400	0.0000	829,402,722	11,762,400	11,719,500	12,788,600	13,170,600	86,800	57,104,189	22,590	37,994,752	12,055
Pit 47 (58)	Pit 47	58.00%	50,449,200	1,972,753,846	446,229,186	169,936,560	0.0000	833,575,660	11,926,200	11,965,200	13,138,400	13,332,600	86,800	57,850,586	22,903	38,458,997	12,230
Pit 48 (59)	Pit 48	59.00%	63,057,100	2,233,819,837	521,628,354	211,299,200	0.0000	873,246,626	13,501,800	14,028,300	19,740,600	15,699,600	86,800	65,543,921	25,821	43,559,797	13,775
Pit 49 (60)	Pit 49	60.00%	63,369,200	2,240,101,605	523,429,491	212,295,280	0.0000	874,146,723	13,544,700	14,059,500	19,901,200	15,777,000	86,800	65,737,885	25,898	43,681,411	13,820
Pit 50 (61)	Pit 50	61.00%	69,881,400	2,363,089,194	558,136,020	233,671,440	0.0000	890,565,718	14,274,000	15,155,400	23,434,400	16,930,800	86,800	69,336,369	27,222	46,088,301	14,522
Pit 51 (62)	Pit 51	62.00%	70,002,300	2,369,053,721	560,313,624	234,155,040	0.0000	891,355,991	14,320,800	15,229,500	23,434,400	16,930,800	86,800	69,536,406	27,317	46,202,387	14,573
Pit 52 (63)	Pit 52	63.00%	70,056,900	2,371,234,836	561,189,759	234,373,440	0.0000	891,615,102	14,340,300	15,264,600	23,434,400	16,930,800	86,800	69,614,066	27,345	46,244,990	14,586
Pit 53 (64)	Pit 53	64.00%	70,102,000	2,374,054,341	562,407,495	234,552,080	0.0000	891,953,610	14,371,500	15,276,300	23,436,600	16,930,800	86,800	69,721,360	27,427	46,295,299	14,634
Pit 54 (65)	Pit 54	65.00%	70,258,400	2,379,031,134	564,272,865	235,078,480	0.0000	892,566,416	14,410,500	15,307,500	23,485,000	16,968,600	86,800	69,888,468	27,489	46,391,945	14,667
Pit 55 (66)	Pit 55	66.00%	70,293,500	2,381,043,736	565,112,067	235,218,880	0.0000	892,810,534	14,433,900	15,319,200	23,485,000	16,968,600	86,800	69,969,545	27,532	46,429,875	14,688
Pit 56 (67)	Pit 56	67.00%	70,352,500	2,384,780,396	566,681,037	235,451,360	0.0000	893,266,390	14,472,900	15,334,800	23,489,400	16,968,600	86,800	70,114,446	27,594	46,502,058	14,716
Pit 57 (68)	Pit 57	68.00%	70,677,700	2,392,358,328	569,356,242	236,537,120	0.0000	894,160,056	14,531,400	15,401,100	23,621,400	17,037,000	86,800	70,363,644	27,694	46,649,309	14,766
Pit 58 (69)	Pit 58	69.00%	70,826,000	2,395,298,884	570,415,911	236,975,920	0.0000	894,496,525	14,558,700	15,424,500	23,623,600	17,132,400	86,800	70,464,522	27,755	46,703,818	14,803
Pit 59 (70)	Pit 59	70.00%	70,880,600	2,397,970,373	571,643,514	237,194,320	0.0000	894,781,630	14,593,800	15,444,000	23,623,600	17,132,400	86,800	70,579,359	27,810	46,754,298	14,830
Pit 60 (71)	Pit 60	71.00%	70,943,500	2,401,691,258	573,352,884	237,442,400	0.0000	895,190,413	14,632,800	15,463,500	23,628,000	17,132,400	86,800	70,726,170	27,848	46,828,424	14,842
Pit 61 (72)	Pit 61	72.00%	76,763,400	2,488,056,829	599,793,129	256,210,500	0.0000	904,344,928	15,159,300	16,224,000	27,049,000	18,241,200	89,900	73,293,298	28,796	48,519,323	15,331
Pit 62 (73)	Pit 62	73.00%	77,218,300	2,498,796,217	603,926,271	257,916,080	0.0000	905,413,176	15,260,700	16,356,600	27,115,000	18,262,800	223,200	73,674,668	28,986	48,721,796	15,442
Pit 63 (74)	Pit 63	74.00%	77,904,800	2,505,520,906	605,258,940	259,989,280	0.0000	906,132,705	15,288,000	16,356,600	27,592,400	18,444,600	223,200	73,847,422	29,038	48,855,512	15,467
Pit 64 (75)	Pit 64	75.00%	77,928,200	2,506,617,380	605,737,041	260,082,880	0.0000	906,246,375	15,299,700	16,368,300	27,592,400	18,444,600	223,200	73,891,859	29,043	48,877,930	15,467
Pit 65 (76)	Pit 65	76.00%	78,397,500	2,513,479,883	607,992,645	261,587,280	0.0000	906,915,577	15,346,500	16,434,600	27,838,800	18,554,400	223,200	74,100,711	29,169	49,006,347	15,545
Pit 66 (77)	Pit 66	77.00%	79,908,400	2,532,113,658	613,335,021	266,369,600	0.0000	908,733,442	15,455,700	16,617,900	28,699,000	18,912,600	223,200	74,644,595	29,378	49,370,818	15,652
Pit 67 (78)	Pit 67	78.00%	81,028,100	2,546,773,194	617,820,996	269,900,560	0.0000	910,139,328	15,553,200	16,680,300	29,433,800	19,137,600	223,200	75,094,272	29,578	49,653,348	15,764
Pit 68 (79)	Pit 68	79.00%	81,112,100	2,548,294,236	618,429,864	270,176,560	0.0000	910,273,445	15,568,800	16,688,100	29,480,000	19,152,000	223,200	75,147,781	29,629	49,679,429	15,797
Pit 69 (80)	Pit 69	80.00%	81,145,600	2,550,357,468	619,460,166	270,309,320	0.0000	910,462,914	15,592,200	16,692,000	29,480,000	19,152,000	229,400	75,232,337	29,659	49,720,034	15,807
Pit 70 (81)	Pit 70	81.00%	81,221,400	2,552,133,041	620,266,101	270,553,320	0.0000	910,615,265	15,611,700	16,695,900	29,510,800	19,173,600	229,400	75,296,228	29,719	49,750,438	15,846
Pit 71 (82)	Pit 71	82.00%	83,103,400	2,572,546,168	625,891,344	276,537,320	0.0000	912,443,970	15,724,800	16,894,800	30,720,800	19,533,600	229,400	75,875,342	29,959	50,146,297	15,986
Pit 72 (83)	Pit 72	83.00%	83,205,100	2,575,554,194	627,276,780	276,928,280	0.0000	912,699,036	15,756,000	16,945,500	30,740,600	19,533,600	229,400	75,989,603	30,019	50,202,669	16,020
Pit 73 (84)	Pit 73	84.00%	83,228,500	2,576,756,664	627,899,415	277,021,880	0.0000	912,799,506	15,775,500	16,949,400	30,740,600	19,533,600	229,400	76,043,898	30,069	50,222,461	16,051
Pit 74 (85)	Pit 74	85.00%	83,232,400	2,577,020,106	628,037,982	277,037,480	0.0000	912,822,061	15,779,400	16,949,400	30,740,600	19,533,600	229,400	76,053,513	30,091	50,225,396	16,067
Pit 75 (86)	Pit 75	86.00%	83,380,000	2,579,430,411	629,054,517	277,508,360	0.0000	913,012,281	15,798,900	16,953,300	30,839,600	19,558,800	229,400	76,134,830	30,127	50,271,830	16,085
Pit 76 (87)	Pit 76	87.00%	83,426,800	2,581,274,396	630,004,752	277,695,560	0.0000	913,157,641	15,818,400	16,980,600	30,839,600	19,558,800	229,400	76,208,239	30,148	50,308,472	16,092
Pit 77 (88)	Pit 77	88.00%	83,454,100	2,582,759,854	630,810,687	277,804,760	0.0000	913,274,745	15,837,900	16,988,400	30,839,600	19,558,800	229,400	76,266,842	30,211	50,332,099	16,136
Pit 78 (89)	Pit 78	89.00%	83,566,400	2,585,991,814	632,447,790	278,253,340	0.0000	913,509,401	15,873,000	17,062,500	30,839,600	19,558,800	232,500	76,389,262	30,298	50,389,859	16,190
Pit 79 (90)	Pit 79	90.00%	83,613,200	2,588,185,037	633,663,459	278,440,540	0.0000	913,670,739	15,900,300	17,082,000	30,839,600	19,558,800	232,500	76,476,080	30,377	50,426,644	16,243
Pit 80 (91)	Pit 80	91.00%	83,628,800	2,589,114,179	634,203,960	278,502,940	0.0000	913,737,211	15,912,000	17,085,900	30,839,600	19,558,800	232,500	76,513,623	30,410	50,442,695	16,262
Pit 81 (92)	Pit 81	92.00%	83,675,600	2,590,787,383	635,103,495	278,690,140	0.0000	913,856,519	15,931,500	17,113,200	30,839,600	19,558,800	232,500	76,581,812	30,445	50,474,383	16,279
Pit 82 (93)	Pit 82	93.00%	83,788,700	2,593,113,976	636,309,531	279,030,220	0.0000	914,014,911	15,962,700	17,124,900	30,839,600	19,629,000	232,500	76,686,382	30,469	50,521,285	16,283
Pit 83 (94)	Pit 83	94.00%	83,800,400	2,593,844,570	636,736,932	279,077,020	0.0000	914,066,828	15,974,400	17,124,900	30,839,600	19,629,000	232,500	76,720,429	30,496	50,534,065	16,297
Pit 84 (95)	Pit 84	95.00%	83,808,200	2,594,314,240	637,014,066	279,108,220	0.0000	914,099,465	15,982,200	17,124,900	30,839,600	19,629,000	232,500	76,740,688	30,523	50,540,984	16,315
Pit 85 (96)	Pit 85	96.00%	83,856,000	2,596,411,691	638,227,902	279,295,920	0.0000	914,239,953	16,013,400	17,136,600	30,839,600	19,630,800	235,600	76,836,002	30,584	50,579,285	16,345
Pit 86 (97)	Pit 86	97.00%	83,910,000	2,598,514,138	639,463,071	279,500,400	0.0000	914,373,364	16,040,700	17,156,100	30,839,600	19,638,000	235,600	76,923,512	30,647	50,616,468	16,382
Pit 87 (98)	Pit 87	98.00%	83,929,500	2,599,328,203	639,941,172	279,578,400	0.0000	914,425,189	16,052,400	17,163,900	30,839,600	19,638,000	235,600	76,960,846	30,662	50,632,283	16,388
Pit 88 (99)	Pit 88	99.00%	84,134,900	2,602,366,050	641,313,075	280,309,120	0.0000	914,612,423	16,087,500	17,222,400	30,949,600	19,639,800	235,600	77,084,616	30,695	50,692,818	16,398
Pit 89 (User)	0	0	87,776,800	2,616,870,881	651,877,863	293,307,140	0.0000	912,817,906	16,337,100	19,039,800	32,045,200	20,066,400	288,300	77,784,738	31,146	50,954,648	16,625

Table 19 below presents the results of the economic cut-off grade (COG) for the optimistic scenario.

Table 19. The economic cut-off grade of the optimistic scenario.

Au Economic COG	2.2455	g/tonne
Cu Economic COG	0.5324%	Percent

Finally, the economic results of the optimistic scenario is shown in Table 20. Moreover, the histogram of the NPV, ore and waste tonnage is shown in Figure 25

Table 20. Economic output of the simulation (Optimistic Scenario).

Global Stats													
Cash	Revenue	Minimum	Maximum	Process Cost	Minimum	Maximum	Mining Cost	Minimum	Maximum	Net Value	Ore Value		
	2,917,598,076	115,230	1,867,302	754,206,765	115,167	216,567	3,760,318,420	4,320	15,600	(1,596,927,109)	2,090,149,311		
	Block Count	Mass											
ORE	4,695	18,310,500											
Waste	408,889	1,059,642,500											
Total	413,584	1,077,953,000											
Strip Ratio	57.8708												
ORE Stats													
	Mass	Au	Au Min	Au Max	Cu	Cu Min	Cu Max	Au R	Au R Min	Au R Max	Cu R	Cu R Min	Cu R Max
	tonnes	g	g/tonne	g/tonne	tonnes	Percent	Percent	g	g/tonne	g/tonne	tonnes	Percent	Percent
ORE	18,310,500	86,934,297	0.4566	9.9856	34,835	0.0003%	0.5994%	56,808,429	0.0662	9.3377	18,547	0.0000%	0.4855%
Waste Stats													
ORE (w)	25,654,200												
WEATH	355,102,000												
SOIL	94,024,800												
FRESH	584,861,500												
Total	1,059,642,500												

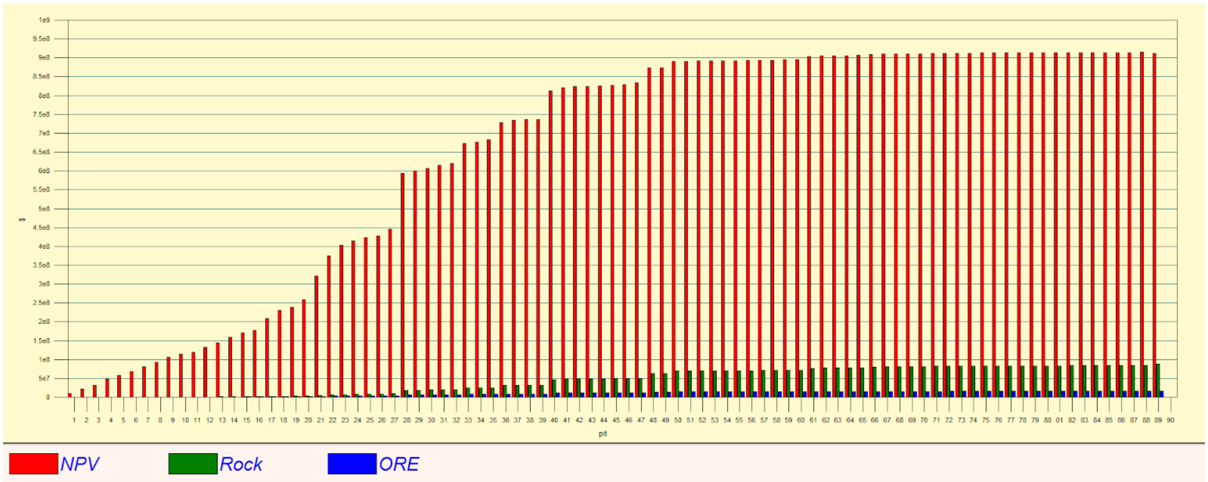

Figure 25. The histogram of NPV, ore and waste tonnage (Optimistic Scenario).

4.3 Pessimistic Scenario

Figures 26 - 28 demonstrate the mining pushbacks of the pessimistic scenario. The software provided three pushbacks for the pessimistic scenario.

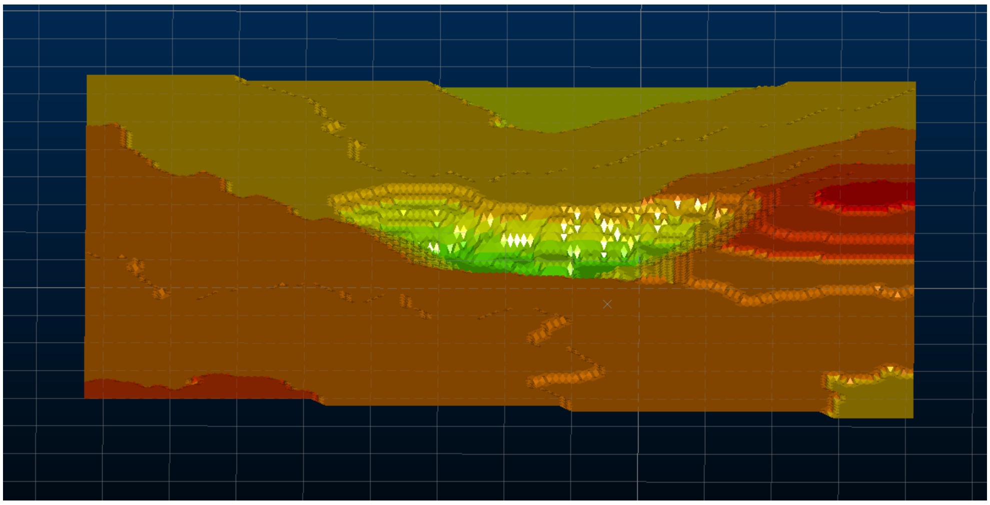

Figure 26. Side view of pushback no. 1 (Pessimistic Scenario).

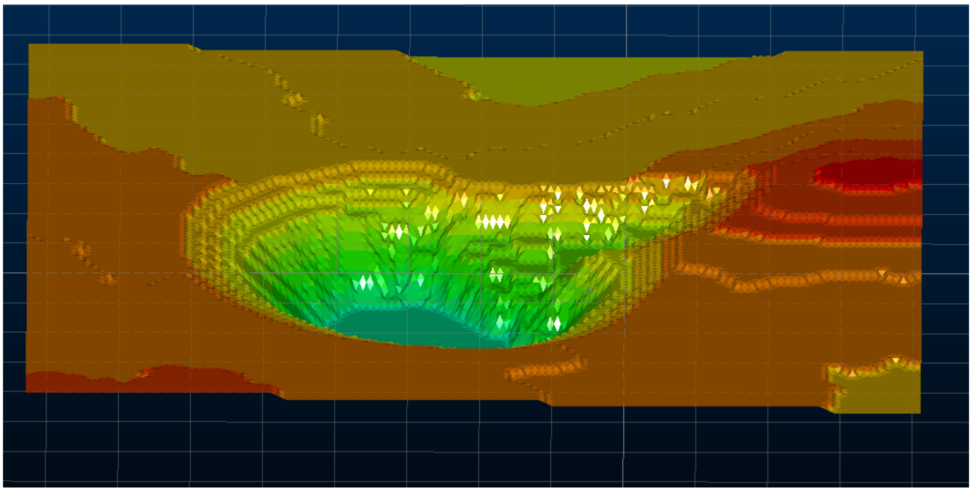

Figure 27. Side view of pushback no. 2 (Pessimistic Scenario).

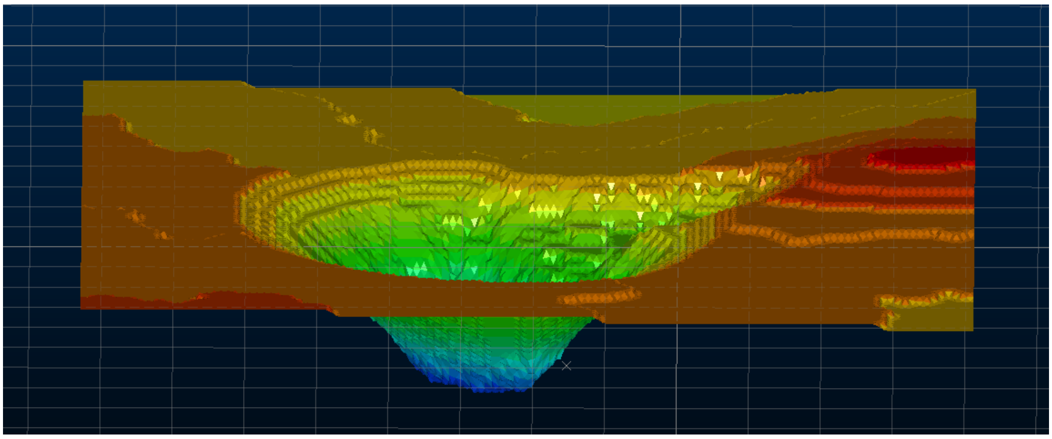

Figure 28. Side view of pushback no. 3 (Pessimistic Scenario).

Table 21 provides the tonnage of ore, waste and profit for each pushback.

Table 21. The tonnage of ore, waste and profit for each pushback (Pessimistic Scenario).

Pushbacks			
Pushback	ORE	Waste	Profit
1	4,071,600	12,505,600	251,596,499
2	3,837,600	42,786,800	77,910,836
3	2,550,600	6,554,000	153,088,150

Then, the final shape for ultimate pit limit is constructed. The figures below demonstrate the graphical illustrations of the ultimate pit limit of the pessimistic scenario.

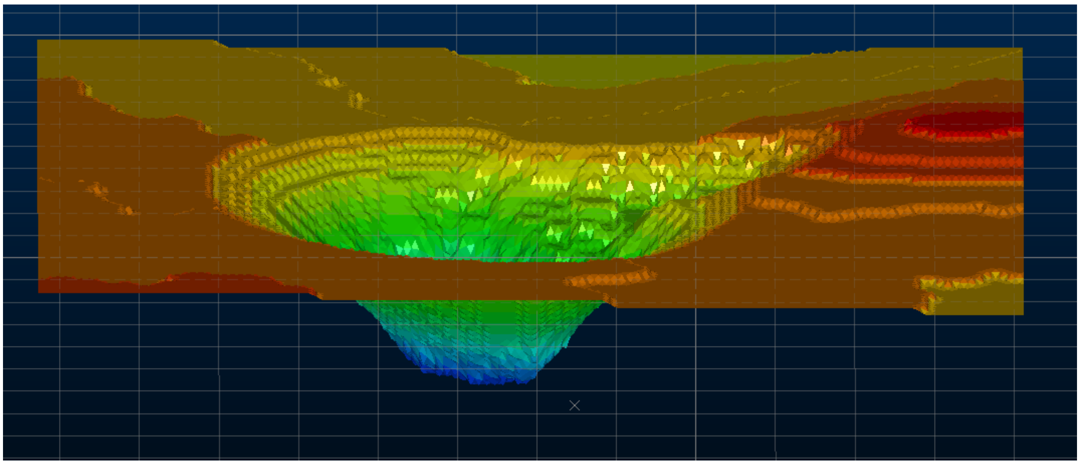

Figure 29. Side view of pit limit (Pessimistic Scenario).

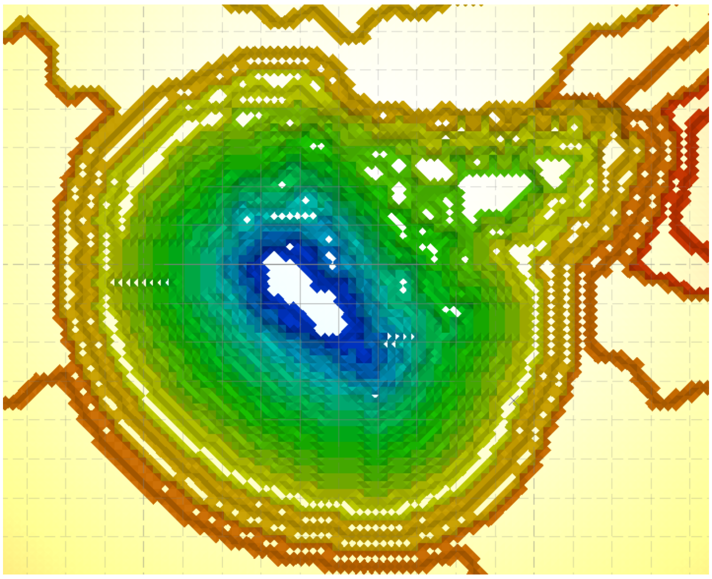

Figure 30. Plan view of pit limit (Pessimistic Scenario).

The lifetime of the project is predicted to be 8 years. Table 22 below shows the results of simulation of 8 years of production – revenue, mining and processing costs for the entire project.

Table 22. Scheduling results by time periods (Pessimistic Scenario).

Year	Rock	Revenue	Processing Cost	Mining Cost	Capital Costs	NPV	ORE	ORE (w)	WEATH	SOIL	FRESH	Au	Cu	Au R	Cu R	Strip
	tonnes	$	$	$	$	$	tonnes	tonnes	tonnes	tonnes	tonnes	g	tonnes	g	tonnes	
1	2,653,800	64,412,674	22,282,299	12,773,520	0.0000	27,742,072	503,100	838,500	0.0000	1,312,200	0.0000	2,711,341	926.4763	1,901,982	481.6312	4.2749
2	4,963,200	125,093,236	44,805,267	24,176,160	0.0000	50,606,193	1,002,300	1,626,300	0.0000	2,334,600	0.0000	5,322,819	1,803	3,696,098	920.1235	3.9518
3	7,760,200	194,047,450	67,710,435	37,237,710	0.0000	76,137,282	1,501,500	2,371,200	0.0000	3,884,400	3,100	8,143,629	2,704	5,739,789	1,386	4.1683
4	15,226,300	458,739,309	163,813,338	78,299,850	0.0000	166,042,526	3,502,200	5,951,400	539,000	5,162,400	71,300	19,194,646	6,175	13,592,169	3,127	3.3476
5	50,069,900	706,685,064	267,345,741	238,171,290	0.0000	155,220,662	5,502,900	9,902,100	17,331,600	17,262,000	71,300	29,784,934	9,985	20,887,407	5,151	8.0988
6	61,306,900	990,156,662	379,114,944	299,826,930	0.0000	218,385,136	7,503,600	14,305,200	22,127,600	17,262,000	108,500	41,278,398	13,866	29,261,229	7,248	7.1703
7	69,035,400	1,266,469,415	499,295,316	344,487,240	0.0000	276,471,034	9,500,400	18,610,800	23,548,800	17,263,800	111,600	52,585,812	17,749	37,415,850	9,343	6.2666
8	72,306,200	1,408,123,367	561,587,442	363,940,440	0.0000	305,516,762	10,459,800	20,779,200	23,691,800	17,263,800	111,600	58,261,172	19,521	41,614,676	10,297	5.9128

Table 23 below shows LG phases of the pessimistic scenario. The highest cumulative NPV is observed in Pit 82 – 356,593,171 $.

Table 23. LG phases (Pessimistic Scenario).

Pit 36 (53)	Pit 36	53.00%	7,449,300	375,068,297	119,300,298	40,436,280	0.0000	193,940,914	2,566,200	3,108,300	0.0000	1,774,800	0.0000	15,042,455	4,679	11,133,764	2,422
Pit 37 (54)	Pit 37	54.00%	7,704,800	383,563,174	122,474,625	41,782,560	0.0000	197,001,901	2,632,500	3,217,500	4,400	1,850,400	0.0000	15,402,975	4,789	11,386,052	2,476
Pit 38 (55)	Pit 38	55.00%	8,745,900	403,851,944	129,183,210	46,456,200	0.0000	203,770,387	2,769,000	3,435,900	66,000	2,475,000	0.0000	16,216,421	4,988	11,993,522	2,573
Pit 39 (56)	Pit 39	56.00%	9,934,800	436,355,765	141,509,394	52,416,720	0.0000	214,362,928	3,018,600	3,876,600	85,800	2,953,800	0.0000	17,576,039	5,493	12,947,684	2,852
Pit 40 (57)	Pit 40	57.00%	10,156,300	445,669,602	145,503,345	53,600,520	0.0000	217,404,412	3,100,500	3,954,600	88,000	3,013,200	0.0000	17,991,950	5,624	13,223,521	2,917
Pit 41 (58)	Pit 41	58.00%	18,139,600	634,250,822	220,182,729	93,557,280	0.0000	266,410,204	4,520,100	6,509,100	1,487,200	5,623,200	0.0000	25,832,220	8,280	18,797,250	4,292
Pit 42 (59)	Pit 42	59.00%	18,378,800	642,138,842	223,316,925	94,789,680	0.0000	268,641,510	4,582,500	6,587,100	1,515,800	5,693,400	0.0000	26,171,284	8,373	19,033,494	4,330
Pit 43 (60)	Pit 43	60.00%	18,669,300	648,352,163	225,701,697	96,249,960	0.0000	270,132,553	4,629,300	6,669,000	1,603,800	5,767,200	0.0000	26,432,365	8,442	19,220,311	4,354
Pit 44 (61)	Pit 44	61.00%	19,151,300	664,245,685	233,054,913	99,011,400	0.0000	273,735,249	4,769,700	6,934,200	1,647,800	5,799,600	0.0000	27,142,217	8,680	19,690,291	4,469
Pit 45 (62)	Pit 45	62.00%	19,226,000	667,439,818	234,596,661	99,447,360	0.0000	274,488,679	4,800,900	6,969,300	1,654,400	5,801,400	0.0000	27,292,163	8,730	19,784,458	4,493
Pit 46 (63)	Pit 46	63.00%	19,288,400	671,132,946	236,526,771	99,821,760	0.0000	275,345,776	4,839,900	6,992,700	1,654,400	5,801,400	0.0000	27,474,633	8,763	19,895,896	4,506
Pit 47 (64)	Pit 47	64.00%	23,218,000	755,278,520	271,674,624	119,856,990	0.0000	292,357,094	5,475,600	8,295,300	2,679,600	6,764,400	3,100	30,984,378	9,926	22,385,579	5,102
Pit 48 (65)	Pit 48	65.00%	23,625,900	765,603,768	276,113,175	121,981,140	0.0000	294,521,481	5,557,500	8,463,000	2,721,400	6,877,800	6,200	31,424,629	10,074	22,690,014	5,182
Pit 49 (66)	Pit 49	66.00%	23,711,700	768,482,977	277,560,192	122,495,940	0.0000	295,046,750	5,584,800	8,521,500	2,721,400	6,877,800	6,200	31,555,312	10,139	22,772,554	5,220
Pit 50 (67)	Pit 50	67.00%	24,869,900	793,146,782	288,674,997	128,376,600	0.0000	299,368,685	5,799,300	8,938,800	2,851,200	7,255,800	24,800	32,636,936	10,582	23,491,270	5,466
Pit 51 (68)	Pit 51	68.00%	25,282,100	802,685,602	293,039,448	130,455,240	0.0000	301,090,274	5,881,200	9,051,900	2,956,800	7,367,400	24,800	33,055,905	10,740	23,771,022	5,550
Pit 52 (69)	Pit 52	69.00%	30,541,700	893,812,433	331,060,587	156,471,270	0.0000	315,322,924	6,540,300	10,315,500	5,007,200	8,650,800	27,900	36,781,566	12,034	26,457,930	6,257
Pit 53 (70)	Pit 53	70.00%	31,302,200	911,009,530	339,086,865	160,434,330	0.0000	317,999,287	6,688,500	10,569,000	5,214,000	8,796,600	34,100	37,532,335	12,325	26,959,798	6,424
Pit 54 (71)	Pit 54	71.00%	31,349,000	912,582,109	339,910,389	160,715,130	0.0000	318,238,879	6,704,100	10,600,200	5,214,000	8,796,600	34,100	37,604,988	12,370	27,003,938	6,451
Pit 55 (72)	Pit 55	72.00%	31,442,600	915,856,204	341,698,968	161,276,730	0.0000	318,710,362	6,739,200	10,658,700	5,214,000	8,796,600	34,100	37,760,708	12,467	27,094,795	6,513
Pit 56 (73)	Pit 56	73.00%	31,505,000	917,975,839	342,856,254	161,651,130	0.0000	319,009,549	6,762,600	10,697,700	5,214,000	8,796,600	34,100	37,864,539	12,518	27,155,757	6,540
Pit 57 (74)	Pit 57	74.00%	46,030,600	1,122,207,393	424,145,007	232,621,320	0.0000	342,090,959	8,178,300	13,919,100	11,499,400	12,396,600	37,200	46,090,206	15,287	33,189,303	8,048
Pit 58 (75)	Pit 58	75.00%	47,104,700	1,141,200,722	433,057,716	237,922,800	0.0000	344,171,362	8,330,400	14,106,300	12,016,400	12,614,400	37,200	46,904,275	15,567	33,750,328	8,188
Pit 59 (76)	Pit 59	76.00%	47,605,300	1,150,014,261	437,184,774	240,478,320	0.0000	345,091,471	8,400,600	14,238,900	12,238,600	12,690,000	37,200	47,280,826	15,693	34,010,766	8,253
Pit 60 (77)	Pit 60	77.00%	47,815,700	1,155,300,590	440,018,046	241,735,290	0.0000	345,605,598	8,447,400	14,391,000	12,240,800	12,690,000	46,500	47,514,111	15,801	34,163,432	8,315
Pit 61 (78)	Pit 61	78.00%	47,913,200	1,158,910,620	442,285,818	242,320,290	0.0000	345,929,873	8,494,200	14,441,700	12,240,800	12,690,000	46,500	47,706,331	15,873	34,268,799	8,350
Pit 62 (79)	Pit 62	79.00%	48,063,600	1,163,070,254	444,708,459	243,187,650	0.0000	346,300,439	8,537,100	14,523,600	12,262,800	12,693,600	46,500	47,906,489	15,938	34,391,575	8,381
Pit 63 (80)	Pit 63	80.00%	48,075,300	1,163,672,098	445,116,321	243,257,850	0.0000	346,353,115	8,544,900	14,527,500	12,262,800	12,693,600	46,500	47,938,633	15,953	34,409,013	8,388
Pit 64 (81)	Pit 64	81.00%	48,111,000	1,165,399,452	446,300,907	243,467,550	0.0000	346,494,621	8,568,300	14,531,400	12,265,000	12,693,600	52,700	48,034,246	15,981	34,460,512	8,398
Pit 65 (82)	Pit 65	82.00%	48,138,300	1,166,663,234	447,167,331	243,631,350	0.0000	346,593,659	8,583,900	14,543,100	12,265,000	12,693,600	52,700	48,099,090	16,015	34,496,225	8,418
Pit 66 (83)	Pit 66	83.00%	48,822,700	1,174,813,278	450,755,058	246,788,310	0.0000	347,183,040	8,650,200	14,609,400	12,577,400	12,933,000	52,700	48,451,492	16,125	34,738,817	8,466
Pit 67 (84)	Pit 67	84.00%	50,046,500	1,191,052,135	458,240,250	252,836,070	0.0000	348,304,877	8,775,000	14,913,600	13,087,800	13,217,400	52,700	49,131,259	16,364	35,216,415	8,600
Pit 68 (85)	Pit 68	85.00%	50,054,300	1,191,544,925	458,609,112	252,882,870	0.0000	348,336,930	8,782,800	14,913,600	13,087,800	13,217,400	52,700	49,160,736	16,374	35,231,121	8,602
Pit 69 (86)	Pit 69	86.00%	50,069,900	1,192,393,068	459,240,405	252,976,470	0.0000	348,388,093	8,794,500	14,917,500	13,087,800	13,217,400	52,700	49,207,003	16,395	35,255,361	8,614
Pit 70 (87)	Pit 70	87.00%	61,788,800	1,326,887,570	518,531,169	310,211,790	0.0000	354,689,347	9,746,100	17,074,200	19,410,600	15,505,200	52,700	54,678,475	18,151	39,239,467	9,537
Pit 71 (88)	Pit 71	88.00%	62,122,400	1,331,137,232	520,287,417	311,843,310	0.0000	355,012,964	9,777,300	17,136,600	19,582,200	15,573,600	52,700	54,851,742	18,221	39,363,258	9,579
Pit 72 (89)	Pit 72	89.00%	62,277,700	1,334,497,228	522,399,696	312,699,990	0.0000	355,159,514	9,812,400	17,206,800	19,619,600	15,586,200	52,700	55,014,867	18,270	39,463,267	9,599
Pit 73 (90)	Pit 73	90.00%	62,316,700	1,335,419,847	522,991,989	312,933,990	0.0000	355,195,553	9,824,100	17,234,100	19,619,600	15,586,200	52,700	55,064,781	18,280	39,491,342	9,601
Pit 74 (91)	Pit 74	91.00%	62,956,000	1,342,381,603	526,213,623	315,991,470	0.0000	355,448,542	9,878,700	17,339,400	19,929,800	15,755,400	52,700	55,356,838	18,401	39,694,290	9,670
Pit 75 (93)	Pit 75	93.00%	66,322,900	1,377,003,065	541,576,776	332,605,110	0.0000	356,363,965	10,124,400	18,064,800	21,731,600	16,349,400	52,700	56,759,264	18,905	40,710,227	9,970
Pit 76 (94)	Pit 76	94.00%	66,352,400	1,378,103,151	542,431,500	332,779,470	0.0000	356,389,724	10,140,000	18,076,500	21,733,800	16,349,400	52,700	56,818,339	18,947	40,739,926	9,997
Pit 77 (95)	Pit 77	95.00%	66,808,200	1,383,149,290	544,864,710	335,098,350	0.0000	356,495,073	10,179,000	18,193,500	21,986,800	16,396,200	52,700	57,030,550	19,021	40,888,493	10,037
Pit 78 (96)	Pit 78	96.00%	66,867,200	1,385,233,696	546,502,827	335,447,070	0.0000	356,530,235	10,206,300	18,220,800	21,991,200	16,396,200	52,700	57,139,787	19,087	40,946,582	10,075
Pit 79 (97)	Pit 79	97.00%	66,906,200	1,386,150,691	547,153,620	335,681,070	0.0000	356,541,800	10,218,000	18,248,100	21,991,200	16,396,200	52,700	57,186,854	19,120	40,971,689	10,095
Pit 80 (98)	Pit 80	98.00%	66,980,300	1,389,187,284	549,673,761	336,125,670	0.0000	356,567,518	10,260,900	18,279,300	21,991,200	16,396,200	52,700	57,353,231	19,207	41,057,622	10,142
Pit 81 (99)	Pit 81	99.00%	67,334,300	1,393,598,573	552,264,102	337,875,990	0.0000	356,591,892	10,303,800	18,345,600	22,169,400	16,462,800	52,700	57,558,233	19,273	41,187,849	10,175
Pit 82 (100)	Pit 82	100.00%	67,349,900	1,394,245,160	552,813,495	337,969,590	0.0000	356,593,171	10,315,500	18,349,500	22,169,400	16,462,800	52,700	57,597,388	19,299	41,205,160	10,192
Pit 83 (User)	0	0	72,219,900	1,408,978,747	561,649,842	363,427,920	0.0000	349,636,216	10,459,800	20,697,300	23,687,400	17,263,800	111,600	58,280,802	19,543	41,638,224	10,315

Table 19 below presents the results of the economic cut-off grade (COG) for the pessimistic scenario.

Table 24. The economic cut-off grade of the pessimistic scenario.

Au Economic COG	3.2227	g/tonne
Cu Economic COG	0.8858%	Percent

Finally, the economic results of the pessimistic scenario is shown in Table 20. Moreover, the histogram of the NPV, ore and waste tonnage is shown in Figure

Table 25. Economic output of the simulation (Pessimistic Scenario).

Global Stats														
Cash	Revenue	Minimum	Maximum	Process Cost	Minimum	Maximum	Mining Cost	Minimum	Maximum	Net Value	Ore Value			
	1,721,121,588	178,081	1,244,632	710,122,491	172,731	274,131	5,640,477,630	6,480	23,400	(4,629,478,533)	934,691,697			
	Block Count	Mass												
ORE	3,261	12,717,900												
Waste	410,323	1,065,235,100												
Total	413,584	1,077,953,000												
Strip Ratio	83.7587													
ORE Stats														
	Mass	Au	Au Min	Au Max	Cu	Cu Min	Cu Max	Au R	Au R Min	Au R Max	Cu R	Cu R Min	Cu R Max	
	tonnes	g	g/tonne	g/tonne	tonnes	Percent	Percent	g	g/tonne	g/tonne	tonnes	Percent	Percent	
ORE	12,717,900	71,093,295	2.5947	9.9856	23,726	0.0003%	0.5994%	50,879,464	0.8460	9.3377	12,491	0.0001%	0.4855%	
Waste Stats														
ORE (w)	31,246,800													
WEATH	355,102,000													
SOIL	94,024,800													
FRESH	584,861,500													
Total	1,065,235,100													

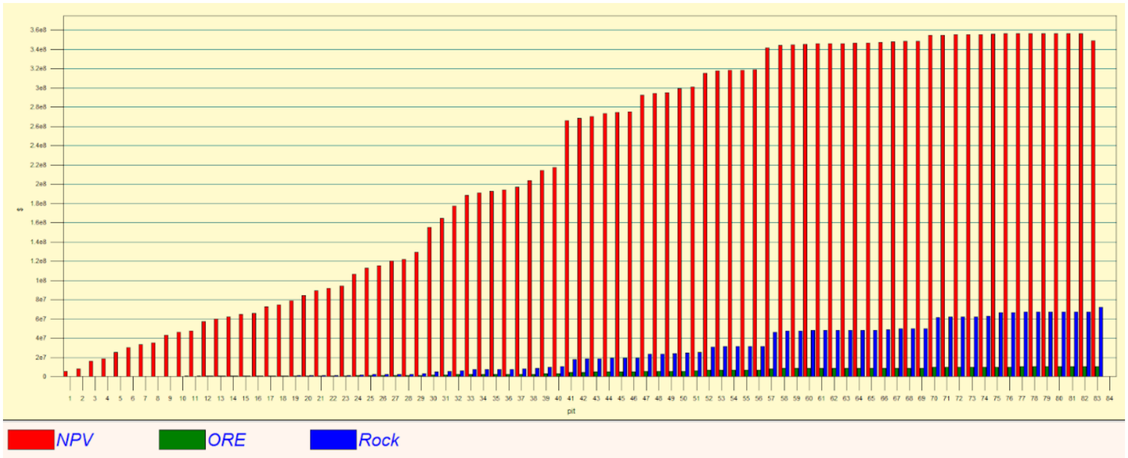

Figure 31. The histogram of NPV, ore and waste tonnage (Pessimistic Scenario).

4.4 Sensitivity Analysis

In the following section, the results of the sensitivity analysis will be provided. The results show how the price variation of gold will affect the economic parameters of the gold-copper open pit mine – Net Present Value (NPV), revenue, and economic cut-off grade. Table 26 present NPV of each price scenario.

Table 26. Sensitivity analysis on Net Present Value.

Sensitivity	Net Present Value (NPV)
20%	$ 858,642,518.00
10%	$ 753,939,427.00
-10%	$ 545,327,291.00
-20%	$ 438,195,130.00

Figure 32 shows the trend of NPV with regard to ore price fluctuations.

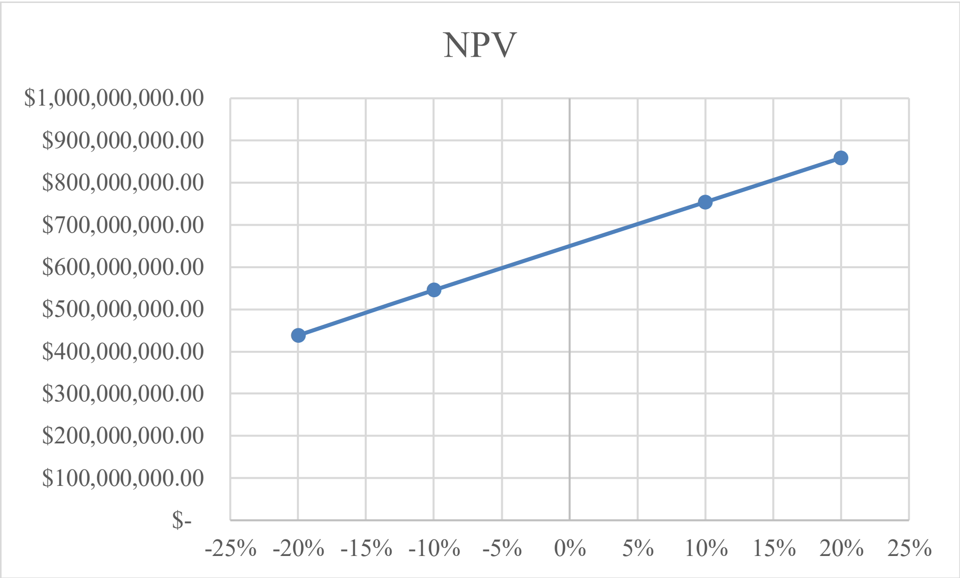

Figure 32. Graph of NPV vs. Price Sensitivities.

Table 27 demonstrates revenue on each price scenario.

Table 27. Sensitivity analysis on revenue.

Sensitivity	Revenue
20%	$ 2,857,571,149.00
10%	$ 2,586,694,785.00
-10%	$ 2,046,707,126.00
-20%	$ 1,774,977,272.00

Figure 33 shows the trend of revenue with regard to ore price fluctuations.

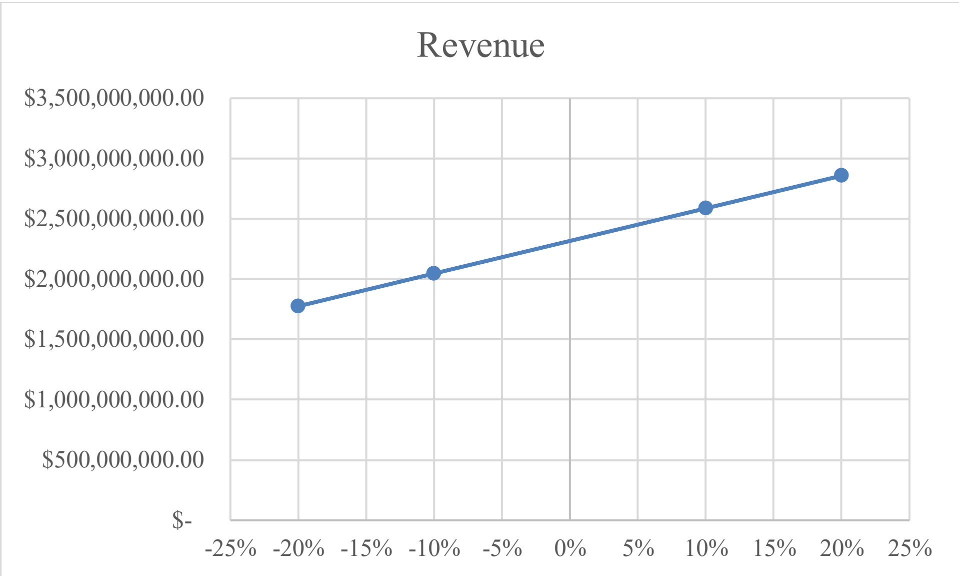

Figure 33. Graph of revenue vs. Price Sensitivities.

Table 28 demonstrates cut-off grade on each price scenario.

Table 28. Sensitivity analysis on cut-off grade.

Sensitivity	Net Present Value (NPV)
20%	$ 858,642,518.00

10%	$ 753,939,427.00
-10%	$ 545,327,291.00
-20%	$ 438,195,130.00

Figure 34 shows the trend of cut-off grade with regard to ore price fluctuations.

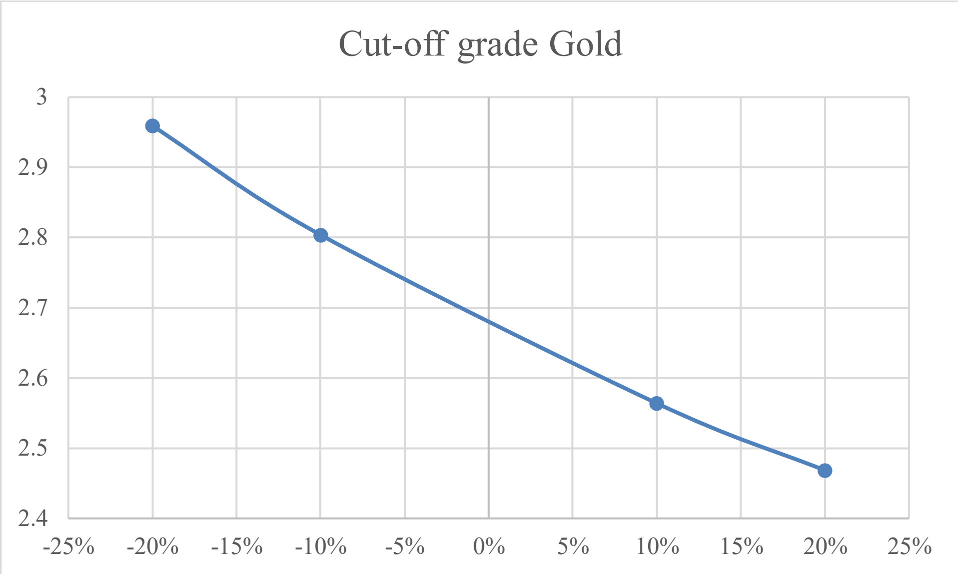

Figure 34. Graph of cut-off grade vs. Price Sensitivities

4. DISCUSSION

In the discussion section, the results of the software simulations will be analyzed and compared. Optimized software simulation provided the experimental results on open-pit mine block sequencing and scheduling with optimistic and pessimistic scenarios. The economic parameters of the base case were given in Table 5. The software provided four mining pushbacks for 10 years of life of mine. The net present value of the project is estimated to be 649,027,644 $. The cut-off grades for gold and copper are 2.6743 g/t and 0.6481% respectively. The optimistic scenario has a 20% increase in the price of the ores (gold and copper), while mining and processing costs have decreased by 20% compared to the base case scenario. The simulation results of optimization provide three mining pushbacks for the same 10 years of life of mine. The estimated NPV of the scenario is supposed to be 914,612,423 $. The cut-off grades for gold and copper are 2.2455 g/t and 0.5324% respectively. Finally, the pessimistic scenario, in contrast, has a 20% decrease in price and a 20% increase in mining and processing costs. The simulation produced three mining pushbacks for 8 years of life of mine. The NPV is expected to be 356,593,171 $ in Pit no. 82. The cut-off grades are 3.2227 g/t and 0.8858% for gold and copper respectively. It could be observed that all three scenarios have unique results for mine planning optimization. Figures 23 and 28 demonstrate the ultimate pit limits for each scenario and it could be found that pit limits for the pessimistic scenario are lower than the optimistic one. The reason is that mining lower blocks are not likely to be profitable as the revenue will not overweight the mining and processing costs. Therefore, the ultimate pit limit of the optimistic scenario is greater than the pessimistic scenario.

There are no significant changes in the number of generated pushbacks among the three scenarios. The software provided three pushbacks on average for the projects. The tonnage of waste generated in the three cases has a slight difference. However, the tonnage of ore is significantly higher in the optimistic scenario (Table 16). This could be explained by the fact that despite ore being mined, it does not process further. It is not profitable to send it to the processing plant.

Price fluctuations had a considerable impact on economic cut-off grades for the scenarios. The pessimistic scenario has a higher cut-off grade (3.2227 g/t and 0.8858% for gold and copper respectively) compared to the base and optimistic scenarios. Higher cut-off grades minimize the number of mining blocks as mining cost is increased in the following scenario. As a result, the sequence of extraction is slightly different from the base case. The approach described in this work is limited to a single processing destination. Therefore, cut-off grades for the following project are constant for the entire mining operations in software computation. Figure 34 shows the trend of the cut-off grade of the gold considering price uncertainties. It could be observed that the cut-off grade is inversely proportional to the price. The higher prices for the ore results in lower cut-off grades and vice versa. Therefore, the mining projects should have flexible cut-off grades for entire life of mine, because the ore price is fluctuating according to the market.

Tables 12, 17, and 22 illustrate the scheduling results of the three scenarios. The software provided 10 years of operation both for the base and optimistic scenarios. While life of mine in the pessimistic scenario is expected to be 8 years. As was mentioned before, mining additional blocks are not as profitable as the optimistic case. Due to a decrease in the price by 20% and an increase in the mining and processing costs by 20%, the overall production years are slightly declined. In the optimistic scenario total mining cost is expected to be 284,411,240 $, while in the pessimistic scenario it is expected to be 363,940,440 $. Moreover, it is important to mention that the mining cost of the optimistic scenario is targeted at 10 years, and 8 years for the pessimistic scenario. The same tendency is observed in the processing costs.

Finally, one of the most crucial parameters is the Net Present Value. The NPV is remarkably affected by price changes. The NPV depends on the price of the materials. Thus, increased price enhances the NPV of the project. Figure 32 demonstrates the relationship between these two components. The NPV of the project grows linearly as the price increase. As a result, the highest NPV is found in optimistic scenario - 914,612,423 $.

The results from Tables 13, 18, and 23 could be considered the important ones in the following thesis paper since it represents the project even in a more detailed way by splitting it into numerous LG phases. These pits are assigned to sequential numbers and provide economic parameters of the blocks. The results showed the highest Net present value is observed in Pit no. 88 in the optimistic scenario (+20% in price) – 914,612,423 $, while the lowest NPV results were in the pessimistic scenario (-20% in price) - 356,593,171 $ in Pit no. 82. Indeed, the Lerchs-Grossman method is still treated as the main foundation for open pit mine planning and sequence of extraction.

5. CONCLUSIONS AND RECOMMENDATIONS

To sum up, block sequencing simulation results were evaluated and compared with modern block sequencing approaches. With the help of Datamine Studio NPVS and a real-world input model, the block sequencing and mine planning areas were simulated. The global literature review section provided several approaches such as direct block sequencing, Lagrangian relaxation, variable elimination, relaxation of integer programming, etc. Moreover, case studies on mine block sequencing related to real-world mining projects were provided. The above optimization methods were implemented in these cases and the results were favorable as well. The direct block sequencing method was a promising one as periods, parameters, and constraints are fed into the optimization model; however, the complexity of the algorithm does not allow the planners to utilize the following method solely. Utilizing DBS with the conventional Lerchs-Grossman method could slightly improve the net present value of the project. The Lagrangian relaxation could positively affect the algorithm of mixed-integer programming, the approach loosens the constraint function by adding Lagrangian multipliers and implementing them in the software algorithm.

The practical part of the thesis was done throughout the gold-copper open pit mine. Three scenarios (base, optimistic and pessimistic) of optimization considering price fluctuations were analyzed and compared. The results provided the Lerchs-Grossman phases for the optimum sequence of extraction of the mining blocks and the general layout of the project through the ultimate pit limit. Moreover, some distinctions between the three cases were compared and explained. Secondly, the software simulation addressed the economic aspects of the above output of the gold-copper open pit mine. It was found that an increase in product price leads to increased NPV of the project. Whereas, an increase in mining and processing costs negatively affects the economic attractiveness of the project. The appropriate sequence of extraction significantly affects the economic viability of the project considering the highest net present value of the mining blocks. Thus, it could be stated that the mining sequence is a crucial part of open-pit mine planning. The further development of the block sequencing software computation could lead to more optimized approaches and thus, enhance the economic aspect of the project.

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