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Economic Sensitivity of Open-Pit Optimization to Commodity Price Regimes: A Deterministic Scenario-Based Analysis

by

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Originality statement

I, Sultanbeibarys Makhanbetkali, hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, or substantial proportions of material which have been accepted for the award of any other degree or diploma at Nazarbayev University or any other educational institution, except where due acknowledgement is made in the thesis. Any contribution made to the research by others, with whom I have worked at NU or elsewhere is explicitly acknowledged in the thesis. I also declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation and linguistic expression is acknowledged.

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ABSTRACT

This study investigates the influence of economic parameter variability on open-pit optimization outcomes within a deterministic mine planning framework. The research focuses on a gold–copper deposit modeled using a block-based representation and optimized through the Lerchs–Grossmann algorithm implemented in Datamine Studio NPVS. The primary objective is to evaluate how different economic environments, defined by commodity price regimes and operating cost variations, affect pit configuration and project valuation.

Three economic scenarios were constructed using historical and forecast commodity price data for gold, copper, and oil. Average annual growth rates were derived for the periods 1980–2000, 2000–2024, and a forecast interval, and applied to adjust baseline metal prices and operating costs. Oil price trends were used as a proxy for operating cost variation. Linear regression analysis was performed to validate long-term price trends and support regime classification.

Deterministic pit optimization was conducted separately for each scenario while maintaining constant geological and technical parameters. The results indicate that economic assumptions have a measurable impact on optimization outcomes. Variations in commodity prices and operating costs influence pit size, ore tonnage, stripping ratio, mine life, and net present value. The scenario representing the 2000–2024 growth regime produced the highest project value, while the earlier historical regime resulted in a reduced economic outcome. The forecast-based scenario yielded results comparable to the base case with moderate deviations.

The findings demonstrate that deterministic optimization outputs are highly sensitive to the economic inputs applied during the modeling process. By integrating regime-based economic scenarios directly into the optimization workflow, this study provides a structured and practical approach for evaluating the robustness of mine planning decisions under alternative economic conditions. The methodology offers an industry-relevant framework for incorporating economic sensitivity analysis into conventional deterministic open-pit optimization.

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1. Introduction

1.1 Background of the study

Open-pit mining is one of the most widely applied methods for the extraction of mineral resources, particularly for large, near-surface deposits of metals such as gold and copper. Profitability of open pit mine relies heavily on the optimization outputs, such as ultimate pit limit, pushback generation and scheduling. Optimization figures the boundaries of economically recoverable material and identifies the scale of the project. Because of this, mine planning includes a plethora of processes, such as geological modelling, engineering design, economic analysis and evaluation to identify whether the extraction of a given deposit is profitable or not by assessing the NPV of the project.

Pit optimization is an important step in open pit mine planning. In this process, the orebody is represented as a block model. The block model divides the deposit into many small blocks. Each block contains geological and economic information. This information includes grade, tonnage, mining cost, and processing cost. The economic value of each block is calculated by comparing the expected revenue from metals with the costs of mining and processing the material. Blocks that generate positive economic value are considered profitable. Blocks with low or negative value may be treated as waste. Optimization algorithms are then used to analyze block values. These algorithms select the combination of blocks that produces the highest economic value. At the same time, they follow geotechnical constraints such as slope stability and mining sequence rules. The final result of this process defines the ultimate pit limit. The ultimate pit limit represents the economically optimal boundary of the open pit under the given economic conditions.

Economic parameters play a critical role in determining the outcome of pit optimization. Metal prices, operating costs, metallurgical recoveries, and discount rates directly influence the economic value assigned to individual blocks within the model.

These parameters, in turn, can vary, and the block could be classified as either ore or waste, thus influencing the geometry of the optimum pit and the amount of ore that can be recovered. Pit optimization, therefore, is not only a technical design process but also involves decision-making in terms of the long-term profitability of the mining venture.

Commodity price is one of the most crucial points among the economic parameters applied during

mine planning. Copper and gold are traded in global markets where prices tend to fluctuate due to the supply and demand curve, geopolitical factors.

Because mining projects typically operate over long time horizons, the economic evaluation of a deposit often relies on assumptions regarding future commodity prices. These assumptions directly affect projected revenues and therefore influence the economic value assigned to blocks within the optimization model.

In conventional mine planning practice, pit optimization is typically performed using deterministic economic inputs. Under this approach, metal prices and operating costs are assumed to remain constant throughout the optimization process. While this assumption simplifies the optimization procedure, it also implies that the resulting pit configuration is optimal only under the specific economic conditions assumed in the model. If commodity prices or operating costs change, the economic value of blocks may also change, potentially altering the extent of the optimal pit and the financial performance of the project.

As a result, the economic environment used during optimization can significantly influence the outcomes of mine planning. Different economic assumptions may produce variations in the volume of material included within the pit, the quantity of recoverable ore, and the overall project value measured through indicators such as net present value (NPV). Evaluating how alternative economic conditions influence optimization outcomes is therefore an important component of strategic mine planning.

1.2 Problem statement

Even though the influence of economic parameters on mine planning outcomes is clear, many traditional optimization workflows rely on a single set of deterministic economic assumptions during the process of identifying ultimate pit limit. In result, optimization output is optimal only for that specific commodity price and cost conditions. Meanwhile, the market is uncertain, hence the commodity price could drop or rise significantly in short periods of time.

In case where economic conditions are different from the initial ones applied for optimization, block economic value inside of the model could be altered, which would also affect the optimal pit limit, and it consequently could decrease NPV of the project. In practice, sensitivity analysis is often used to examine the effect of parameter variation on project valuation. Nevertheless, such

type of analysis is mostly performed subsequent to the optimization process, and that means that pit remains without changes.

Limitation in traditional deterministic mine planning methods is created by this, and there the influence of alternative economic environments on optimization outputs may not be evaluated. Understanding how variations in commodity price regimes and operating costs affect the optimized pit limits and project valuation can therefore provide valuable insights for strategic mine planning and economic decision-making.

1.3 Aim and Objectives of the study

The aim of this study is to evaluate the influence of different economic environments on open-pit optimization outcomes using a deterministic mine planning framework. The research investigates how variations in commodity price regimes and operating costs affect pit configuration, operational indicators, and project valuation.

To achieve this aim, the following objectives were defined:

- To make regression analysis of historical commodity price trends for gold, copper, and oil in order to identify characteristic economic regimes.
- To determine average annual growth rates for these commodities using historical and forecast price data.
- To construct economic scenarios based on the identified growth regimes and apply them to metal prices and operating costs.
- To perform deterministic open-pit optimization using a gold–copper block model within the Datamine NPVS environment.
- To compare the resulting optimization outcomes across scenarios using operational and economic indicators such as pit size, ore tonnage, stripping ratio, mine life, and NPV.

1.4 Significance of the study

The results of this study contribute to understanding the role of economic assumptions in deterministic mine planning. Because pit optimization relies on predefined economic inputs, the resulting pit configuration and project valuation depend directly on the economic conditions assumed during optimization. By evaluating multiple economic regimes derived from historical

and forecast price data, this research provides insight into how variations in commodity price environments may influence the economic boundary of a mineral deposit.

Analysis that was conducted in this thesis could allow mine planning engineers to assess sensitivity of optimization results to alternative conditions of economic regime. By implementing results from this study, strategic planning decisions could enhance decision making process by evaluating how commodity price and operating cost changing could affect the scale and profitability of mine.

In addition, the methodological approach applied in this study demonstrates a practical method for incorporating economic scenario analysis within a conventional deterministic optimization framework. Rather than replacing standard optimization algorithms with computationally complex stochastic methods, the study evaluates alternative economic regimes using tools commonly applied in industry mine planning software. This provides a practical and industry-relevant framework for assessing economic variability within deterministic mine planning workflows.

1.5 Scope of the Study

This study focuses on the economic evaluation of open-pit optimization outcomes under different commodity price regimes using a deterministic modeling framework. The analysis is based on a gold–copper block model dataset implemented within the Datamine Studio NPVS mine planning software.

Three economic scenarios were constructed using historical and forecast commodity price data for gold, copper, and oil. Average annual growth rates were calculated for each regime and applied to adjust baseline commodity prices and operating costs used in the optimization model. The resulting economic parameters were implemented as fixed inputs during the optimization process. The study evaluates the impact of these economic regimes on key operational and financial indicators, including pit size, ore and waste tonnage, stripping ratio, mine life, and net present value.

The scope of the research is limited to deterministic optimization. Geological uncertainty,

stochastic price simulation, and dynamic year-by-year commodity price variation are not incorporated in the analysis. Additionally, geotechnical parameters and metallurgical recovery assumptions are kept constant across all scenarios in order to isolate the influence of economic parameter variation on optimization outcomes.

2. Literature review

2.1 Open-Pit Mine Optimization

Open pit mine optimization is fundamentally an economic decision-making process in which the objective is to determine the ultimate pit limit that maximizes the economic value of a mineral deposit. The optimization framework is based on the representation of the orebody as a block model, where each block is assigned an economic value derived from expected revenues and associated costs. The economic value of a block is typically calculated as the difference between the revenue generated from the contained metal and the combined costs of mining, processing, and selling that material. This economic block valuation forms the basis for determining which blocks should be included within the final pit.

The determination of the ultimate pit limit is commonly performed using graph-theory-based algorithms, most notably the Lerchs–Grossmann (LG) algorithm. The LG method defines the most profitable pit configuration while respecting geotechnical slope constraints and precedence relationships between blocks. As noted in recent research, the LG algorithm is widely employed in commercial mine planning software for generating ultimate pit limits and pushback phases (Madziwa et al., 2025). The algorithm provides an optimal solution to the pit limit problem under the assumption that all input parameters, including metal price and operating costs, are fixed during the optimization process. The economic nature of pit optimization is emphasized in classical mine planning literature. Open pit design is not solely a geometric or engineering exercise, but an integration of technical feasibility and economic viability. Economic evaluation procedures are applied at multiple stages of mine planning, from initial strategic assessment to detailed scheduling (Runge, 1998). The selection of reserve blocks, determination of production strategies, and overall project evaluation are all influenced by economic criteria (Runge, 1998). This reinforces the principle that pit optimization is inherently linked to financial performance indicators such as net present value.

In practical applications, commercial mine planning tools generate nested pit shells by adjusting economic parameters, typically through revenue factors. These nested pits allow planners to evaluate alternative development stages within the overall economic framework (Madziwa et al., 2025). However, the optimization remains dependent on predetermined economic inputs. For

example, in the study integrating variable commodity prices into the LG algorithm, it was shown that conventional constant-price models can underestimate or overestimate project net present value under different price trends. Specifically, during upward price trends, the constant price model underestimated net present value by approximately 35%, while during downward trends it overestimated net present value by nearly 30% (Madziwa et al., 2025). These findings demonstrate the economic sensitivity of pit optimization outcomes to input assumptions. These differences suggest that project valuation based on constant price inputs may not fully reflect exposure to market variability.

Foundational open pit planning literature further establishes that economic constraints directly control reserve definition and mine development strategies. The process of selecting blocks for extraction is governed by economic thresholds, and changes in economic parameters directly influence the extent of the final pit (Hustrulid et al., 2013).

Strategic mine planning emphasizes that nested pit shells generated through parametric optimization provide the structural basis for designing mining phases that maximize early cash flow and improve overall project net present value. Real pit shells, together with bench configurations, can be used to construct pushbacks that prioritize regions with favorable combinations of grade and stripping ratio, thereby influencing the timing of revenue generation (Whittle et. al, 2005). The sequencing of these shells enables life-of-mine simulation in which tonnes, grades, cash flows, and discounted cash flows are calculated according to specified throughput limits. This demonstrates that pit geometry is directly linked to economic performance through cash flow timing, reinforcing the central role of economic assumptions in defining optimal extraction strategies.

In summary, the open pit mine optimization framework integrates block valuation, geotechnical slope constraints, and financial evaluation within a mathematically rigorous structure. The Lerchs–Grossmann algorithm determines the economically optimal pit limit based on predefined price and cost parameters, thereby establishing a deterministic basis for pit configuration. This structural dependence on assumed economic parameters forms the foundation upon which subsequent financial evaluation and planning decisions are constructed.

2.2 Economic Evaluation in Mining Projects

Economic evaluation is an integral part of mining project analysis and helps in identifying whether a mineral resource can be economically developed under certain technical and market conditions. The most widely applied technique used for mining project evaluation is discounted cash flow analysis, which takes into account the time value of money and helps in creating a systematic approach for determining the long-term financial viability of a project (Runge, 1998; Rudenno, 2012).

Discounted cash flow analysis relies on the concept that cash flows at different times cannot be compared directly without discounting. Future cash flows are then transformed into their present value equivalents using a suitable discount rate. Runge (1998) explained that discounted cash flow analysis requires a detailed schedule of capital expenditures, production rates, revenues, operating costs, taxation, and salvage values, all expressed over the life of the mine. In result, net present value represents the aggregate value of discounted cash inflows minus discounted cash outflows. A positive net present value indicates that the project generates returns above the selected discount rate.

The application of discounted cash flow methods in mining projects requires careful treatment of capital expenditure and operating cost estimation. According to Rudenno (2012), project valuation is strongly influenced by the forecasting of commodity prices, production, operating costs, and discount rates. The valuation of projects combines geological, technical, and economic data into a financial model. Mining projects, which have long-term time spans, make the discount rate a critical factor in net present value calculations. Discount rates are expected to represent the opportunity cost of capital and risk characteristics of the project (Runge, 1998; Rudenno, 2012).

Operating costs and commodity prices are considered critical variables in discounted cash flow valuation. Dehghani and Ataee-pour (2012) highlight that economic uncertainty, particularly in metal prices and operating costs, can cause a substantial change in the evaluated value of a mining project. In their analysis of the Çayeli copper mine, the net present value was calculated for three scenarios: certainty in both price and operating cost, uncertainty in metal price only, and uncertainty in both price and operating cost. The analysis showed that the inclusion of uncertainty

in both price and operating cost assumptions changed the evaluated project value from deterministic assumptions (Dehghani & Ataee-pour, 2012). This suggests that the outcome of economic evaluation is directly sensitive to the treatment of uncertain inputs.

Similarly, studies incorporating variable commodity prices into the Lerchs–Grossmann optimization framework demonstrate that deterministic constant-price assumptions can materially distort project valuation (Madziwa et al., 2025). By comparing constant-price and forecast-based price inputs, the authors show that financial outcomes derived from static assumptions may deviate significantly from those obtained under variable market conditions. These findings reinforce the dependence of discounted cash flow results on the economic parameters embedded within the optimization process.

Economic evaluation is not only used in project approval but is also incorporated into the mine planning process. According to Runge (1998), economic evaluation methods are used in the strategic evaluation, selection of reserve blocks, comparison of equipment, and overall project evaluation. Consequently, discounted cash flow analysis is not a distinct financial calculation but is instead incorporated into the technical planning process of open pit mining.

In conclusion, economic evaluation in mining projects is mainly carried out using discounted cash flow techniques that take into account capital costs, operating costs, price, and discount rates. The net present value is the main indicator of economic viability. However, the accuracy of economic evaluation is highly dependent on the assumptions made in the valuation of price and cost. There is evidence from the literature that shows deterministic assumptions made in economic inputs have a material impact on economic evaluation results. This confirms the significance of structured sensitivity analysis in mining economics, which is discussed in the next section.

2.3 Sensitivity analysis in Mining Economics

Sensitivity analysis is a methodological technique that can be used to examine the effect of changes in input parameters on the output of an economic model. In mining economics, sensitivity analysis can be used to examine the effect of changes in commodity price, cost, capital expenditure, rate of production, and discount rate on financial variables such as net present value and internal rate of return. Due to the long-term nature of mining projects, sensitivity analysis can be used as a systematic approach to determine the important economic factors.

Sensitivity analysis can be categorized into mathematical, statistical, and graphical techniques based on the type of model and the purpose of the sensitivity analysis. According to Frey and Patil (2002), there are ten techniques of sensitivity analysis, which include four mathematical techniques, five statistical techniques, and one graphical technique. Authors emphasize that no single method is universally superior and that multiple approaches may be required to increase confidence in identifying key drivers of model outcomes (Frey & Patil, 2002). Although their review is not mining-specific, it establishes the theoretical foundation for sensitivity analysis as a systematic tool for model verification, validation, and prioritization of influential inputs.

In mining applications, sensitivity analysis is often implemented as one-factor analysis, where a single parameter is varied while others remain constant. Fomin and Bazarova (2015) describe sensitivity analysis in open pit design as a single-factor method aimed at determining how strongly project performance indicators change in response to variations in initial parameters. The authors define sensitivity in terms of elasticity, calculated as the ratio of the percentage change in a project indicator to a one percent change in the influencing variable. They note that relative sensitivity analysis commonly evaluates parameter changes of approximately 10 percent to determine the degree of project risk associated with each variable (Fomin & Bazarova, 2015).

This elasticity-based interpretation allows parameters to be ranked according to their economic influence.

The influence of cut-off selection on project valuation is further demonstrated through Lane's theory of cut-off optimization, which incorporates both cash costs and

time-related pseudo-costs associated with production delay (Whittle et. al, 2005). In a ten-million-tonne scenario, varying the cut-off for the first one million tonnes from 0.20 to 0.45 increased total project net present value from US\$128.3 million to US\$132.4 million, despite a reduction in immediate cash flow. Increasing the cut-off further to 0.70 reduced total net present value to US\$131.2 million (Whittle et. al, 2005). The analysis also shows that the net present value of the remaining nine million tonnes changes by approximately 6 percent with each half-year shift at a 12 percent discount rate, demonstrating the interaction between cut-off policy, timing, and discounting in determining total project value.

Runge (1998) integrates sensitivity analysis within discounted cash flow evaluation and project comparison. Sensitivity graphs are used to illustrate how net present value varies with changes in key parameters, enabling decision-makers to assess the robustness of investment decisions. This approach highlights that sensitivity analysis is not separate from financial modeling but is embedded within economic evaluation procedures.

Dynamic stochastic optimization approaches have been proposed to address the limitations of static two-stage formulations in mining complex planning. Del Castillo and Dimitrakopoulos (2019) develop a multistage stochastic integer programming framework that incorporates dynamic capital expenditure decisions within long-term production scheduling of open pit mining complexes. The proposed method allows strategic plans to branch when a representative proportion of geological scenarios support alternative investment decisions, thereby embedding operational flexibility within the life-of-mine schedule. In the presented copper mining complex case study, a 42 percent probability of investing in a secondary crusher in year three resulted in the design branching into two feasible strategic plans. The dynamic formulation generated an increase in project net present value of approximately US\$170 million relative to the static two-stage solution, corresponding to a 3 percent improvement at the P50 level and an 8 percent increase at the P90 level. These results demonstrate that incorporating dynamic decision-making under geological uncertainty can materially influence valuation outcomes and improve the capacity of optimization models to respond to evolving information.

The importance of sensitivity analysis becomes more evident when economic uncertainty is explicitly modeled. Dehghani and Ataee-pour (2012) demonstrate that incorporating uncertainty

in metal prices and operating costs affects the evaluated net present value of a mining project. Their application of the binomial tree technique illustrates that economic variables do not remain constant over time, and that deterministic assumptions may misrepresent project value. Similarly, Madziwa et al. (2025) show that deterministic constant-price models can materially distort net present value under changing price trends. These quantified results indicate that the sensitivity of financial outputs to economic inputs is substantial.

Beyond traditional one-factor approaches, sensitivity analysis is also incorporated within broader risk assessment frameworks in mining. Banda (2019) combines analytic hierarchy process methodologies, expert questionnaire survey analysis, and sensitivity analysis to determine sensitive risk events in mining projects. In this context, sensitivity analysis is employed to determine the risk events that have the most significant impact on overall project risk, thus facilitating the prioritization of risk mitigation plans. While this methodological approach goes beyond the scope of strictly financial considerations, it confirms the importance of sensitivity analysis as a systematic approach to the identification of influential variables in complex mining systems.

2.4 Commodity Price Uncertainty in Mine Planning

Commodity price variability is one of the most significant sources of economic uncertainty in mining projects. Since open pit optimization and financial evaluation depend directly on projected metal prices, fluctuations in market conditions can substantially influence reserve estimation, pit limits, and net present value outcomes. Conventional mine planning approaches tend to consider constant or average commodity prices in the calculation of ultimate pit limits and financial viability (Madziwa et al., 2025; Rudenno, 2012).

Metal prices are affected by supply and demand, macroeconomic factors, and market speculation, which results in uncertain long-term forecasting. According to Dehghani and Ataee-pour (2012), future metal prices are among the most important economic uncertainties in the valuation of mining projects. In practice, it is common to use historical averages, such as three-year average prices, to avoid overly optimistic projections; however, this approach assumes price stability over the life of mine (Dehghani & Ataee-pour, 2012).

Recent research has examined the consequences of incorporating price variability directly into mine planning models. Madziwa et al. (2025) integrated forecasted gold prices into the Lerchs–Grossmann optimization framework on an annual basis and compared constant-price and variable-price approaches. Their results showed that during upward price trends, the constant-price model underestimated net present value by approximately 35 percent. Conversely, during periods of declining prices, the deterministic model overestimated net present value by nearly 30 percent. In contrast, the price-forecast-based model reduced estimation deviations, producing values closer to observed outcomes (Madziwa et al., 2025). These findings demonstrate that pit optimization and financial evaluation outcomes are highly sensitive to price assumptions.

Rudenno (2012) further notes that commodity price forecasting is central to mining valuation, as projected revenues are directly linked to expected market prices. Given that mining projects typically span long operational periods, even moderate variations in price assumptions can produce substantial differences in discounted cash flow calculations. This reinforces the dependence of net present value on accurate representation of market conditions.

However, despite the proven impact of economic input variability, the standard approach to open pit optimization is still based on the use of constant economic inputs. The Lerchs-Grossman algorithm, as used in most commercial software, is based on the use of pre-defined price assumptions to determine the boundaries of the pit (Madziwa et al., 2025). This means that the ultimate pit design will be based on a deterministic economic environment.

Commodity price uncertainty is a fundamental aspect of mining project valuation and open pit optimization. Empirical studies have shown that constant price considerations can have a material impact on net present value calculations, especially in scenarios where market trends are subject to change. The reliance on deterministic price inputs in optimization frameworks highlights the importance of structured economic sensitivity evaluation within open pit mine planning.

2.5 Operating cost uncertainty in Mine Planning

Operating costs represent a major component of total project expenditure in open pit mining and directly influence discounted cash flow calculations and net present value outcomes. These costs

include drilling, blasting, loading, hauling, processing, energy consumption, maintenance, and labor. Economic models of evaluation consider operating costs as fixed or predetermined values over the life of mine (Runge, 1998; Rudenno, 2012).

The sources of uncertainty in operating costs include energy price variability, changes in labor costs, technological changes, and macroeconomic factors. Dehghani and Ataee-pour (2012) consider operating cost uncertainty as a major but relatively less investigated economic factor in mine project evaluation. They observed that in many previous investigations, the variability of metal prices was modeled while the operating costs were assumed to be known parameters. In their investigation of the Çayeli copper mine, the net present value was estimated using three scenarios: price and operating cost certainty, price uncertainty only, and joint price and operating cost uncertainty. The binomial tree method was used to model economic uncertainty. The outcome of the investigation showed that joint consideration of price and operating cost uncertainty affected the estimated project value compared with deterministic models (Dehghani & Ataee-pour, 2012). This indicates that treating operating costs as fixed parameters may reduce the robustness of economic evaluation in long-term mining projects.

Estimating operating costs is also covered in the literature on mining economic planning. According to Runge (1998), operating cost curves are considered essential components of cash flow analysis, and it is important to recognize that production levels, machine utilization, and maintenance needs have a direct impact on cost estimates. Likewise, Rudenno (2012) observes that operating costs are affected by considerations such as fuel prices, exchange rates, and cost inflation.

Cost variability is not limited to long-term macroeconomic changes but may also arise from operational adjustments within the mine plan. Runge (1998) demonstrates through equipment cost scheduling examples that variations in machine life, maintenance cycles, and utilization rates modify ownership and operating cost structures. These cost components are embedded in discounted cash flow models and influence the resulting economic indicators.

Sensitivity analysis approaches applied in open pit design further quantify the effect of cost changes. Fomin and Bazarova (2015) describe relative sensitivity analysis as a method for

determining how performance indicators respond to parameter changes, often evaluating variations of approximately 10 percent in input variables. Elasticity coefficients are used to measure the proportional impact of cost variation on production or economic indicators (Fomin & Bazarova, 2015). Within broader risk assessment frameworks, operating cost variability is treated as part of project risk exposure. Banda (2019) incorporates sensitivity analysis into a structured risk assessment model to identify volatile risk events in mining projects, linking cost-related factors to overall project risk evaluation.

The reviewed literature demonstrates that operating cost assumptions are embedded within both optimization and financial evaluation models. Variability in these costs affects discounted cash flow outputs and project valuation, yet many deterministic optimization frameworks continue to rely on fixed operating cost parameters.

2.6 Research Gap and Study positioning

The reviewed literature demonstrates that conventional open pit optimization and financial evaluation frameworks are built on fixed economic parameters embedded within the Lerchs–Grossmann algorithm and discounted cash flow modeling (Madziwa et al., 2025; Runge, 1998; Rudenno, 2012). Although these deterministic structures are widely applied in commercial mine planning practice, documented evidence shows that project valuation outcomes can deviate materially under alternative price and cost assumptions (Madziwa et al., 2025; Dehghani & Ataee-pour, 2012). These deviations highlight the sensitivity of net present value to economic variability but do not resolve the structural reliance of optimization workflows on predefined inputs.

Sensitivity analysis methods are commonly used to quantify the responsiveness of financial indicators to parameter changes (Frey & Patil, 2002; Fomin & Bazarova, 2015). However, in most mining applications, such analyses are conducted after pit limits and production schedules have already been determined. As a result, sensitivity analysis evaluates outcome variability without modifying the deterministic configuration of the optimization model itself. This separation between optimization structure and economic variability limits the integration of uncertainty within conventional planning workflows.

Advanced stochastic optimization approaches incorporating geological and investment uncertainty have demonstrated measurable improvements in economic performance. Del Castillo and Dimitrakopoulos (2019) report that dynamic multistage stochastic programming increased project net present value relative to traditional two-stage formulations, with improvements of approximately 3 percent at the P50 level and 8 percent at the P90 level. Despite these quantified benefits, such formulations remain computationally complex and are not routinely implemented in standard Lerchs–Grossmann-based planning environments.

Furthermore, while commodity price variability has received considerable analytical attention, operating cost uncertainty is frequently treated as fixed within optimization frameworks, despite evidence that joint price and cost variability can materially influence valuation outcomes (Dehghani & Ataee-pour, 2012; Rudenno, 2012). This reinforces the broader limitation of deterministic economic assumptions embedded in widely used optimization procedures.

Within this context, the present study addresses the identified structural separation between deterministic pit optimization and economic variability assessment by applying a structured economic sensitivity framework directly to a conventional open pit optimization model. Rather than replacing the deterministic Lerchs–Grossmann structure with computationally intensive stochastic formulations, this research systematically evaluates the impact of combined metal price and operating cost variations on project valuation outcomes. By quantifying the magnitude and direction of net present value deviations under alternative economic scenarios, the study provides a practical and industry-relevant approach to assessing valuation robustness within widely applied deterministic planning workflows.

3. Methodology

3.1 Research Design and Methodological Framework

This study adopts a deterministic economic optimization framework to evaluate how historically derived and forecast-based commodity price regimes influence open pit optimization outcomes. The methodological design integrates three core components: (i) deterministic Lerchs–Grossmann (LG)–based pit optimization implemented in Datamine NPVS, (ii) regime-based adjustment of metal prices and operating costs using statistically derived growth rates, and (iii) regression analysis applied as a validation tool for long-term commodity price trends.

Open pit optimization is conducted using Datamine NPVS, which applies a Lerchs–Grossmann algorithm to determine the ultimate pit limit that maximizes economic value. The objective function is net present value (NPV), calculated through discounted cash flow principles. The optimization remains deterministic, meaning that economic parameters are predefined and fixed within each scenario. This structure is consistent with conventional industry practice and allows direct evaluation of how alternative economic assumptions affect pit configuration and project valuation.

To address the structural dependence of deterministic optimization on fixed economic inputs, this study introduces regime-based economic scenarios. Instead of applying arbitrary price variations, average annual growth rates are calculated from historical commodity price data and forecast datasets. These growth rates are used to adjust base gold and copper prices, as well as operating costs. Operating cost variation is linked to oil price growth, based on the assumption that fuel and energy constitute a primary driver of mining operational expenditure. Each scenario therefore represents a distinct economic regime derived from empirical data.

Regression analysis is conducted separately for gold, copper, and oil price series. The purpose of regression is not to determine growth rates, but to examine the statistical significance and directional consistency of long-term price trends within each defined period. This provides analytical support for regime segmentation and ensures that scenario construction is grounded in observed market behavior. Statistical outputs of the regression analysis are presented in the

Results section. A linear regression model was selected to provide a simplified representation of long-term price trends. Although commodity prices may exhibit non-linear and cyclical behavior, linear regression allows consistent identification of overall trend direction across different periods. The objective of this analysis is not to accurately model price dynamics, but to evaluate general trend behavior and support the classification of economic regimes used in scenario construction

Within each scenario, adjusted prices and operating costs remain constant during optimization. No dynamic year-by-year price scheduling or stochastic simulation is applied. The methodological focus is therefore on comparing deterministic optimization outcomes under alternative, empirically derived economic environments.

The overall workflow of the study follows a structured sequence: data acquisition; calculation of annual growth rates; regression-based trend validation; economic parameter adjustment; deterministic optimization in Datamine NPVS; and comparative evaluation of resulting pit limits and NPV outcomes. This framework ensures methodological transparency, reproducibility, and direct alignment with the research objective of assessing the sensitivity of open pit optimization to economically justified input regimes.

3.2 Dataset Description

The study is based on two primary data categories: (i) a gold–copper block model used for open pit optimization and (ii) historical and forecast commodity price datasets used for economic parameter determination.

Mining Dataset:

A gold–copper block model from a Kazakhstani mine was imported into Datamine NPVS for economic optimization. The model represents a discretized deposit containing gold and copper grade information used for block economic value calculation. The block model was applied directly within the optimization workflow without geological re-estimation or structural modification.

The purpose of the mining dataset in this study is strictly economic evaluation. No additional geological interpolation, grade estimation, or design constraint modeling was conducted. The

block model serves as the fixed geological framework upon which alternative economic regimes are tested.

Commodity Price and Oil Data:

Annual real commodity price data for gold, copper, and oil covering the period 1980–2024 were used to determine historical growth rates. The dataset was obtained from the Commodity Markets Outlook historical annual database of World Bank.

Only annual real prices were used to ensure consistency across long-term economic regimes. The dataset was structured chronologically and separated into two historical periods:

1)1980–2000

2)2000–2024

In addition, a forecast prices for the next 3 yearst was used to construct the third economic scenario.

All datasets were processed to compute annual percentage growth rates using consecutive yearly observations. No smoothing, interpolation, or transformation of the raw annual price series was performed prior to growth rate calculation.

Oil price data were included to model operating cost variability, based on the assumption that fuel and energy costs represent a primary contributor to mining operational expenditure.

This dataset structure enables construction of regime-based economic scenarios grounded in historical commodity behavior, which are subsequently implemented within the deterministic optimization framework. The historical dataset consists of 45 annual observations for each commodity covering the period 1980–2024. Gold prices are expressed in USD per troy ounce, copper prices in USD per metric ton, and oil prices in USD per barrel.

3.3 Price Trend Analysis and Growth Rate Determination

Annual real price data for gold, copper, and oil covering the period 1980–2024 were used to derive historical growth characteristics. The dataset was segmented into two historical regimes: 1980–2000 and 2000–2024. A third regime was constructed using forecast data.

Annual Growth Rate Calculation

Annual growth rates were calculated using the percentage change between consecutive yearly observations:

$$g = \frac{(P_t - P_{t-1})}{P_{t-1}} \quad (1)$$

where:

P_t = commodity price in year t

P_{t-1} = commodity price in the previous year

This calculation was applied separately to gold, copper, and oil price series.

For each defined period, the average annual growth rate was computed as the arithmetic mean of the yearly growth values. These averages represent the characteristic growth behavior of each economic regime.

The resulting average growth rates were used to adjust base commodity prices and operating costs according to:

$$P_{adj} = P_{base} \times (1 + g_{avg}) \quad (2)$$

where:

g_{avg} = Average annual growth rate for specific scenario

Gold and copper prices were adjusted individually using their respective growth rates. Operating costs were adjusted using oil price growth rates.

No compounding across mine life was applied. Growth was incorporated as a one-time adjustment to define static scenario-specific economic inputs.

Regression Analysis of Commodity Prices

Linear regression analysis was conducted separately for gold, copper, and oil price series using time as the independent variable and commodity price as the dependent variable.

The regression model is expressed as:

$$P_t = \alpha + \beta t + \varepsilon_t \quad (3)$$

where:

α = intercept

β = trend coefficient

t = time (year)

ε_t = error term

The purpose of regression analysis was not to determine growth rates, but to evaluate the statistical significance and direction of long-term price trends within each regime. This procedure provides analytical validation of structural differences between historical periods and supports the regime-based scenario framework.

Statistical outputs of the regression analysis are presented in the Results section.

3.4 Economic Model Formulation

The economic model defines how block-level revenues and costs are calculated and how project value is evaluated under each economic scenario. The formulation integrates metal prices, operating costs, and discounted cash flow principles within the deterministic optimization environment of Datamine NPVS.

Baseline commodity prices were defined using the average real prices for the period 2023–2025, representing post-pandemic market conditions. Based on annual averages from the World Bank Commodity Price Data the baseline prices used in the economic model were 2,591 USD per troy ounce for gold, 9,193 USD per metric tonne for copper, and 75.6 USD per barrel for crude oil.

These baseline values were used as reference inputs for the economic model, while scenario-specific prices and operating costs were derived by applying the growth rates described in Section 3.3. Gold prices obtained from the commodity database are reported in USD per troy ounce. Since gold grades in the block model are expressed in grams per tonne, the price was converted to USD per gram prior to input into the optimization model using the standard conversion of 1 troy ounce = 31.1035 grams.

$$Price_g = \frac{Price_{oz}}{31.1035} \quad (4)$$

Revenue Calculation

Revenue is calculated at block level using gold and copper grades contained within the block model. For each block, metal revenue is determined from grade, corresponding commodity price, and metallurgical recovery. A selling cost equivalent to 2.5% of the commodity price was applied to both gold and copper. This cost was incorporated as a proportional deduction from gross revenue, resulting in net revenue values used in block economic evaluation

$$R = (P \times (1 - 0.025)) \times r \times g \times T \quad (5)$$

where:

P: Price of commodity

r: Metallurgical Recovery

g: Grade

T: Tonnes of materials being processed

Gold and copper prices are adjusted according to the average growth rates derived for each regime, as described in Section 3.3. Within each scenario, adjusted prices remain constant during the optimization process.

Operating Cost Modeling

Operating costs include mining and processing expenditures applied within the optimization model. To incorporate economic variability, operating cost adjustments are linked to oil price growth rates.

A base operating cost of USD 15 per tonne is assumed for the economic model. This value represents a typical operating cost level for open pit mining operations, which commonly ranges between USD 10 and USD 20 per tonne. The base value serves as the reference cost used to construct scenario-specific operating costs.

Operating costs for open-pit mining operations vary depending on factors such as ore characteristics, processing requirements, mine scale, and energy prices. Feasibility studies of large open-pit metal mines provide useful benchmarks for typical operating expenditures. For example, the feasibility study of the Troilus gold–copper project reports life-of-mine operating costs of approximately 11.60 USD/t for mining, 5.64 USD/t for processing, and 1.82 USD/t for general and administrative expenses, resulting in a total operating cost of approximately 19.06 USD per tonne of ore processed (Troilus Mining Corp., n.d.). Similar magnitudes of operating costs are reported in studies of open-pit copper operations, where major cost components such as crushing, milling, and mining activities together constitute the majority of total operating expenditures (Mboyo et al., 2025). Based on these reported industry values, a total operating cost of 15 USD per tonne was assumed in this study as a representative mid-range estimate for combined mining and processing costs in an open-pit operation.

Operating costs in mining operations are typically composed of several major components, including mining, mineral processing (milling), and general and administrative (G&A) expenses. Analysis of published cost data from multiple hard-rock mining operations shows that mining and milling costs constitute the largest portions of total operating expenditures. Curry, Ismay, and Jameson (2014) analyzed operating costs across numerous mines and found that mining and milling costs each account for approximately 43–45% of total operating costs, while G&A costs represent a smaller portion, typically around 10–14%. Since G&A costs are generally treated as fixed overheads and are not directly applied to individual blocks in pit optimization models, they were excluded from the economic block model used in this study. Consequently, the assumed total operating cost of 15 USD per tonne was divided equally between mining and processing components, resulting in mining and processing costs of 7.5 USD/t each.

Operating cost adjustments across scenarios are determined using the average oil price growth rate derived for each economic regime. Oil price behavior is used as a proxy for operational cost variation, based on the assumption that fuel and energy expenditures constitute a major component of mining operating costs.

The adjusted operating cost for each scenario is therefore calculated using the base operating cost and the corresponding oil price growth rate.

$$C_{adj} = C_{base} \times (1 + g_{avg(oil)}) \quad (6)$$

C_{base} = base operating cost

$\bar{g}_{oil}$ = average annual oil price growth rate for the specified regime

Block Economic Value

Block economic value is determined as the difference between revenue and operating cost. Blocks generating positive economic value contribute to pit optimization, while negative-value blocks may be excluded depending on the configuration produced by the optimization algorithm.

$$V_{block} = R - C_{adj} \quad (7)$$

where:

R = block revenue

C_{adj} = adjusted operating cost

Discounted Cash Flow and Net Present Value

Project valuation is performed using discounted cash flow principles. Net present value (NPV) is calculated by discounting annual net cash flows over the life of the project using a specified discount rate.

$$NPV = \sum_{t=1}^T \frac{CF_t}{(1+r)^t} \quad (8)$$

where:

CF_t = net cash flow in period t

r = discount rate

T = project life

The objective of the optimization in Datamine NPVS is to maximize discounted economic value, thereby identifying the ultimate pit limit that yields the highest NPV under each economic scenario.

The economic model remains deterministic. Prices and operating costs are fixed within each scenario, and variability is introduced only through regime-based adjustment of economic inputs. This structure allows direct comparison of optimization outcomes under alternative historically and forecast-based economic conditions.

3.5 Open Pit Optimization Procedure in Datamine NPVS

Open pit optimization was conducted in Datamine Studio NPVS using a structured sequence consisting of block model configuration, economic model generation, and ultimate pit limit determination under deterministic economic inputs.

Block Model Configuration

A new single-mine project was created in the NPVS environment. The gold–copper block model was imported and configured within the software.

During the import process, relevant attributes were assigned to their respective roles within the optimization framework. The slope region field was defined to control geotechnical constraints. Gold (Au) and copper (Cu) were defined as economic elements, with gold specified as grade (g/t) and copper specified as percentage (%). Density was assigned to enable conversion between volume and tonnage.

Rock types were classified into ore and waste categories based on lithological coding. Slope regions were defined according to rock type classification. Inter-ramp slope angles were assigned separately for each region as follows:

- Ore: 55°
- Soil: 25°
- Weathered rock: 45°
- Fresh rock: 55°

These slope definitions were applied prior to economic evaluation and optimization.

Economic Model Definition

The economic block model was generated using the cost-based economic modeling option within the software. Economic parameters were entered manually for each scenario.

Scenario-specific gold and copper prices, adjusted according to regime-based growth rates, were defined in the price settings. Operating costs were defined in the mining settings and modified according to oil-based growth adjustments corresponding to each scenario.

Mining Cost Adjustment Factors were assigned for each rock type to reflect relative cost differences. Processing costs were applied only to ore material using a defined processing method. Metallurgical recovery for gold and copper was implemented using grade-dependent polynomial functions. For gold, recovery is defined as zero for grades below 1 g/t and follows a cubic polynomial function for higher grades. Similarly, copper recovery is defined as zero below 0.1% grade and follows a cubic polynomial relationship above this threshold. These functions were directly implemented within the NPVS processing parameters. Below is the recovery formulas for gold and copper respectively.

$$Recovery_{Au} = \left\{ \frac{0.0207 * Au^3 - 1.3576 * Au^2 + 22.58 * Au - 17.204}{100} \right\} \quad (9)$$

$$Recovery_{Cu} = \left\{ \frac{1713 * Cu^3 - 2236 * Cu^2 + 987.83 * Cu - 76.667}{100} \right\} \quad (10)$$

Bench-based cost adjustment factors were not applied in this study.

After defining all economic inputs, the economic model was executed. The software calculated block net values and internally determined economic cut-off grades based on the defined revenue and cost structure.

Ultimate Pit Optimization

Ultimate pit limit determination was performed using the optimization module based on the Lerchs–Grossmann algorithm. The selected objective was maximization of discounted cash flow.

A discount rate of 15% was applied within the optimization time settings and used in the discounted cash flow calculations for all scenarios. This value is consistent with typical industry practice for mining project evaluation. Slope constraints were enforced according to previously defined slope regions and corresponding angles. A minimum bottom width constraint of 40 meters was applied.

The optimization process generated a series of nested pit shells (LG phases). For each phase, cumulative net present value was calculated within the reporting environment.

The optimal ultimate pit was selected as the phase that produced the maximum cumulative NPV. This pit configuration represents the economically optimal limit under the specified scenario-specific economic parameters.

The procedure was repeated independently for each of the three economic scenarios. Geological parameters, slope angles, recovery functions, and discount rate remained constant across scenarios. Only metal prices and operating costs were varied.

The optimization framework remained deterministic, with no stochastic simulation or dynamic time-based price scheduling applied.

Pushback Generation

Following identification of the optimal ultimate pit shell based on maximum cumulative NPV, pushback generation was performed within the optimization environment. The selected ultimate pit phase served as the final pit limit for pushback design.

Pushbacks were generated using the pit shell corresponding to the maximum cumulative NPV.

The maximum number of pushbacks was defined to divide the total ore tonnage into staged mining phases. Mining width control parameters were specified to ensure operationally feasible working widths between consecutive pushbacks.

Tonnage control parameters were applied to distribute ore extraction approximately evenly across pushbacks, while bench-level constraints were defined to guide vertical sequencing. Alternative pushback generation settings were evaluated within the deterministic framework to identify the configuration producing improved economic performance.

The resulting pushbacks represent sequential mining stages within the final pit geometry. Each pushback inherits the economic assumptions defined in the corresponding scenario, and no additional economic parameter variation was introduced during pushback generation.

Production Scheduling

Production scheduling was conducted after pushback generation to determine life-of-mine performance under defined extraction constraints. The scheduling module was configured using annual planning periods.

Operational parameters included the number of working days per year and ore production capacity constraints. Variable consumption rates were applied to represent staged production targets during different phases of the mine life.

The scheduler allocated ore and waste extraction across pushbacks while respecting capacity limits and economic block values generated during optimization. The resulting schedule produced an estimated life-of-mine duration and annual production profile.

Scheduling remained deterministic. Production capacities, economic parameters, and block values were predefined within each scenario. No stochastic production variability, operational uncertainty, or adaptive market response was modeled.

3.6 Economic Scenario Construction

Three economic scenarios were constructed to evaluate the influence of historically derived and forecast-based commodity growth regimes on deterministic open pit optimization outcomes. The scenarios differ only in the adjusted values of gold price, copper price, and operating cost. All

geological parameters, slope angles, recovery functions, and discount rate remained constant across scenarios.

The construction of each scenario followed a consistent procedure:

1. Annual real price data for gold, copper, and oil were segmented into defined regimes.
2. Annual growth rates were calculated using consecutive yearly observations.
3. The average annual growth rate was computed for each commodity within the specified period.
4. Base commodity prices and base operating costs were adjusted using the corresponding average growth rate.
5. The adjusted values were used as fixed economic inputs in the optimization model.

Prices and operating costs remained constant within each scenario during optimization. No compounding across the life of mine and no year-by-year variation were applied.

Scenario 1: 2000–2024 Growth Rate

In the first scenario, average annual growth rates were calculated using annual real price data covering the period 2000–2024. Separate growth rates were derived for gold, copper, and oil. Gold and copper prices were adjusted individually using their respective growth rates. Operating costs were adjusted using the oil growth rate, based on the assumption that oil price behavior reflects variations in energy-related mining costs.

The adjusted economic parameters represent a modern commodity cycle regime characterized by post-2000 market behavior.

Scenario 2: 1980–2000 Growth Rate

The second scenario was constructed using annual real price data covering the period 1980–2000. Growth rates were calculated separately for gold, copper, and oil. Adjusted metal prices and operating costs reflect the historical commodity environment of the earlier period. This regime provides a contrasting economic context relative to the post-2000 market structure.

Scenario 3: Forecast-Based Regime

The third scenario was developed using forecast commodity data. Average annual growth rates were derived from forecast series for gold, copper, and oil. The resulting adjusted prices and operating costs represent a forward-looking economic environment. This scenario allows evaluation of optimization sensitivity under projected market conditions.

3.7 Assumptions and Limitations

The methodological framework of this study is subject to several assumptions and structural limitations, which define the scope and interpretation of the results. First, the optimization framework is fully deterministic. Metal prices, operating costs, recovery functions, and slope parameters are predefined within each scenario and remain fixed during optimization. No stochastic simulation, probabilistic modeling, or Monte Carlo analysis was applied.

Second, commodity price variability is represented through average annual growth rates derived from historical and forecast data. Growth is incorporated as a one-time adjustment to base prices and operating costs. No year-by-year price evolution or compounding across the life of mine is modeled. Consequently, short-term volatility and cyclical fluctuations are not explicitly represented. Commodity price behavior is approximated using linear regression trends, which may not fully capture non-linear and cyclical market dynamics.

Third, operating cost variation is assumed to follow oil price growth rates. This approach is based on the premise that fuel and energy expenditures are major contributors to mining operational costs. However, other cost drivers such as labor, consumables, and equipment depreciation are not independently modeled.

Fourth, no mining dilution was considered in the optimization model. A mining recovery of 90% was assumed to account for ore losses during extraction. Metallurgical recovery for gold and copper was applied using grade-dependent recovery functions defined within the economic model.

Fifth, geotechnical parameters, including slope angles and slope regions, are assumed constant across all scenarios. No sensitivity analysis was performed on slope configuration or rock mass behavior.

Sixth, the geological block model is treated as fixed and accurate. No geological uncertainty, grade estimation error, or resource classification variability is incorporated into the optimization process.

Finally, the study includes not only ultimate pit limit determination but also pushback generation and production scheduling within the deterministic framework. Pushbacks were generated based on the selected optimal ultimate pit, and production scheduling was performed to estimate life-of-mine performance under defined capacity constraints.

4. Results

4.1 Commodity Price Growth Rates

The average growth rates for gold, copper, and oil were computed using historical and forecasted prices available from the datasets used in the methodology. The historical prices are divided into two regimes: one from 1980 to 2000 and another from 2000 to 2024. The third regime is obtained from the forecast prices from 2025 to 2027.

Table 1 presents the calculated average annual growth rates used for scenario construction.

Table 1. Average annual commodity price growth rates used for scenario construction

Scenario	Gold Growth	Copper Growth	Oil Growth
1980-2000	−4.06%	−0.96%	+0.23%
2000-2024	+10.99%	+8.76%	+5.75%
Forecast (2025-2027)	−0.22%	+1.54%	−1.72%

The calculated growth rates indicate that the historical period 1980–2000 is characterized by negative average growth for both gold and copper prices, while oil prices exhibit a slight positive growth rate. In contrast, the period 2000–2024 shows positive growth rates for all three commodities. The forecast regime presents relatively moderate growth behavior, with a small positive growth rate for copper and slight negative growth rates for gold and oil.

These growth rates were subsequently applied to adjust baseline commodity prices and operating costs in the economic scenarios used for deterministic open pit optimization.

4.2 Commodity Prices for Base case

Baseline commodity prices used in the economic model were determined using recent market conditions. The base case prices for gold, copper, and crude oil were calculated as the average real prices over the period 2023–2025. This period was selected to represent current commodity market conditions and to provide a reference price environment for the economic model.

Annual commodity price data was obtained from the World Bank Commodity Price Data database. The base case price for each commodity was calculated by averaging the annual prices for the three-year period according to the following expression:

$$P_{base} = \frac{(P_{2023} + P_{2024} + P_{2025})}{3} \quad (11)$$

Using this approach, the following baseline prices were obtained.

Table 2. Base case commodity prices

Commodity	Base Price
Gold	2591 USD per troy ounce

Copper	9193 USD per metric tonne
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These baseline prices served as the reference inputs for the economic model. Scenario-specific commodity prices and operating costs were derived by applying the growth rates presented in Section 4.1.

4.3 Regression analysis of Commodity Prices Trends

Linear regression analysis was conducted to evaluate the direction and statistical characteristics of long-term price trends for gold, copper, and oil within the defined historical regimes. The regression models were estimated using time as the independent variable and commodity price as the dependent variable. The results provide statistical indicators describing the strength and direction of price trends for each commodity within the periods 1980–2000 and 2001–2024.

Gold Price Regression Results

The regression analysis for gold prices was performed separately for the two historical periods in order to examine differences in long-term price behavior. Table 4.3 presents the regression statistics obtained for gold price trends.

Table 3. Regression statistics for gold price trends.

Period	Multiple R	R ²	Adjusted R ²	F statistic	Significance F	Slope(β)	P-Value	Observations
1980-2000	0.8913841	0.7945657	0.783753449	73.487024	5.91523E-08	-20.437979	5.91523E-08	21
2001-2024	0.9332242	0.8709075	0.865039688	148.42047	2.97217E-11	63.7838867	2.97217E-11	24

The regression results indicate a negative slope coefficient during the period 1980–2000 and a positive slope coefficient during the period 2001–2024. The coefficient of determination values suggests a strong relationship between time and gold price within both periods. The statistical significance values indicate that the regression models for both periods are statistically significant.

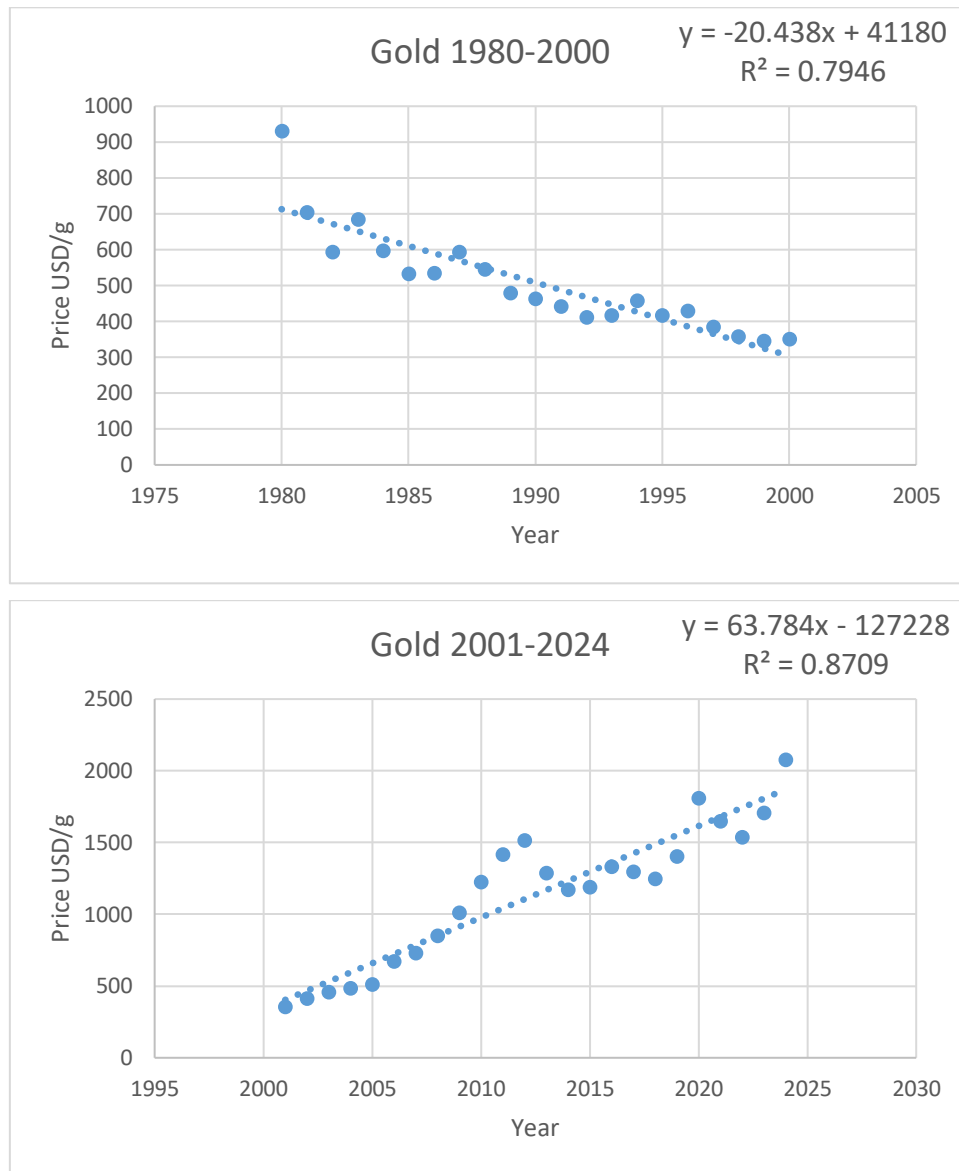


Figure 1. Linear regression trends for gold prices in the periods 1980–2000 and 2001–2024.

Copper Price Regression Results

Regression analysis was also conducted for copper prices in order to evaluate long-term trend behavior across the two historical regimes. Table 4 presents the regression statistics for copper price trends.

Table 4. Regression statistics for copper price trends.

Period	Multiple R	R ²	Adjusted R ²	F statistic	Significance F	Slope(β)	P-Value	Observations
1980-2000	0.218570	0.0477732	-0.00234396	0.9532302	0.341166464	-16.547409	0.34116	21
2001-2024	0.6695156	0.4482511	0.423171652	17.873213	0.000346	181.604787	0.00034	24

The results of the regression analysis indicate that the slope coefficient is negative during the

period 1980-2000 and positive during the period 2001-2024. The coefficient of determination values indicates that the relationship between time and copper prices is weak during the period 1980-2000 and stronger during the period 2001-2024. The statistical significance values indicate that the regression model for the period 2001-2024 is statistically significant, while the regression model for the period 1980-2000 is not statistically significant.

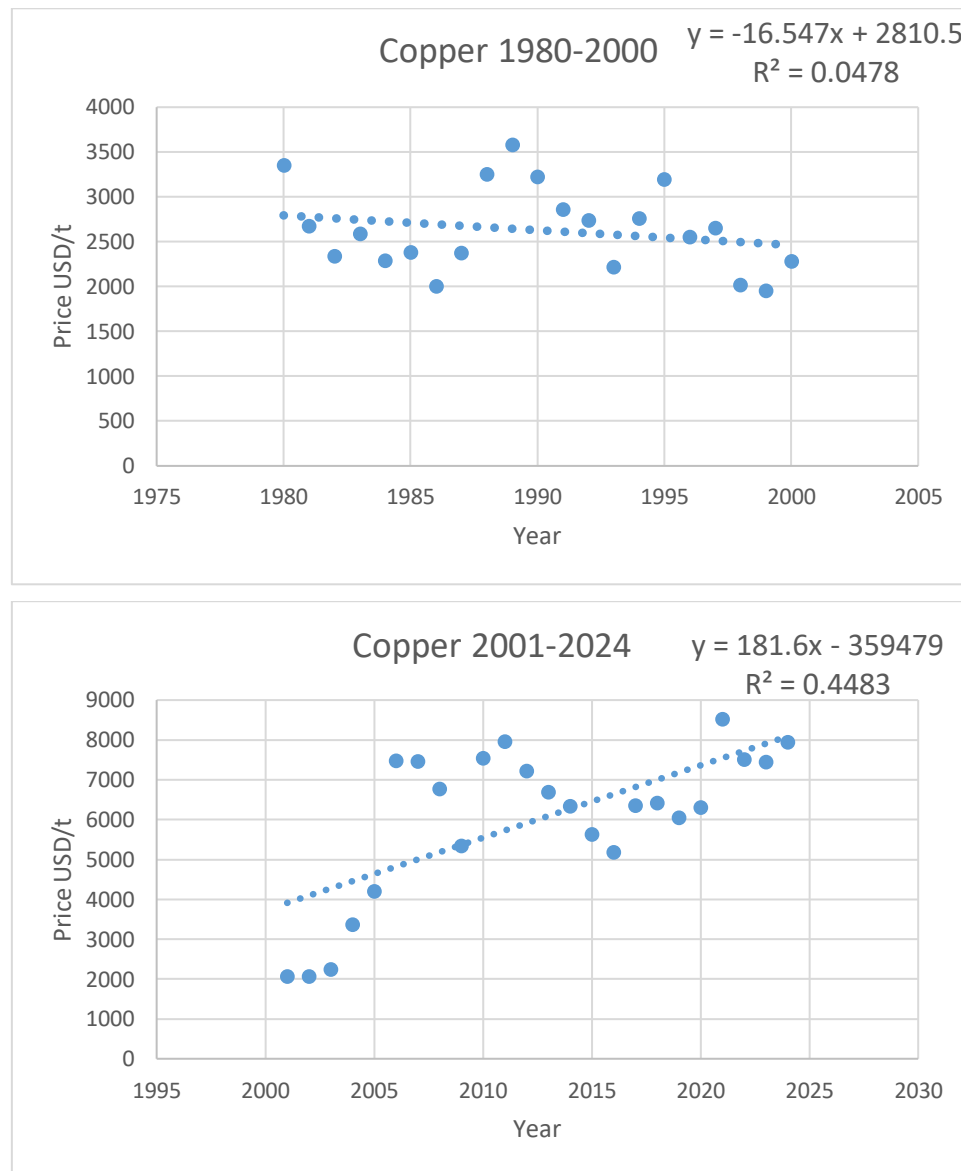


Figure 2. Linear regression trends for copper prices in the periods 1980–2000 and 2001–2024.

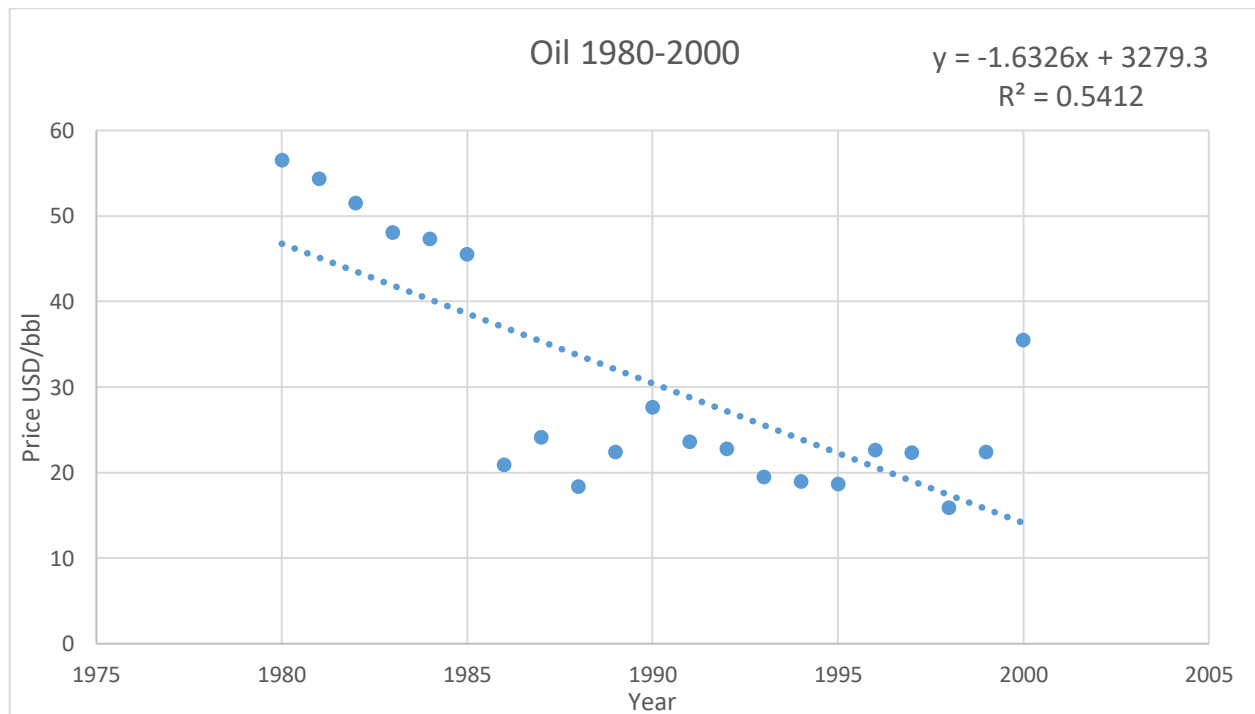
Oil Price Regression Results

Regression analysis was performed for crude oil prices to examine the long-term trend behavior of the energy price series used as a proxy for operating cost variation. Table 5 summarizes the regression statistics obtained for oil price trends.

Table 5. Regression statistics for oil price trends.

Period	Multiple R	R ²	Adjusted R ²	F statistic	Significance F	Slope(β)	P-Value	Observations
1980-2000	0.7356559	0.5411896	0.51704171	22.411443	0.00014438	-1.6325904	0.00014	21
2001-2024	0.2602572	0.0677338	0.025358114	1.5984112	0.21935954	0.74197867	0.21935	24

From the regression results, it is clear that the slope coefficient is negative during the period 1980-2000, while it is positive during the period 2001-2024. It is also clear that the coefficient of determination values indicate that there is a moderate relationship between time and oil prices during the earlier period, whereas there is a weak relationship between time and oil prices during the later period. It is also clear that the statistical significance values indicate that the regression model is statistically significant during the period 1980-2000, whereas it is not statistically significant during the period 2001-2024.



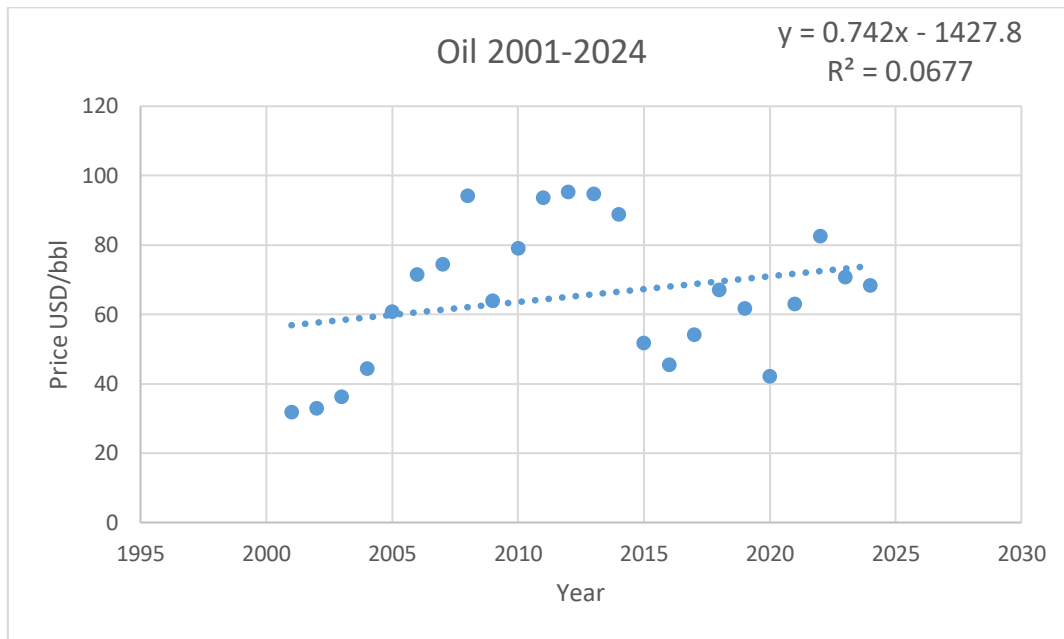


Figure 3. Linear regression trends for crude oil prices in the periods 1980–2000 and 2001–2024. The relatively low R^2 values observed for copper (1980–2000) and oil (2001–2024) indicate weak linear relationships between price and time, reflecting higher volatility and the influence of external market factors. This does not contradict the use of regression, but rather highlights structural differences in commodity price behavior across regimes.

4.4 Economic Scenario Parameters

This section presents the economic input parameters applied in the open pit optimization model for the base case and the three economic scenarios defined in the study. The parameters include gold price, copper price, and operating cost, which were adjusted according to the growth rate regimes described in Section 4.1.

Base case prices were calculated as the average real prices for the period 2023–2025. These values represent the reference economic environment used in the optimization model. Scenario-specific economic parameters were subsequently obtained by applying the corresponding commodity price and oil price growth rates to the baseline values.

Table 6. Economic parameters used in the optimization model for the base case and scenario regimes.

Case	Gold price (USD/g)	Copper price (USD/t)	Operating cost (USD/t)
Base case	83.30	9193	15
Scenario 1	59.64	8477	15.3

Scenario 2	226.25	20207	24.9
Scenario 3	81.76	10494	13

The table shows the variation in commodity prices and operating costs across the evaluated economic regimes. The base case represents the reference price environment derived from recent commodity price data. Scenario 1 reflects the historical growth characteristics of the period 1980–2000, resulting in lower gold and copper prices relative to the base case and a marginal increase in operating cost. Scenario 2 corresponds to the commodity growth regime observed during the period 2001–2024 and produces the highest gold and copper prices together with an increased operating cost. Scenario 3 represents the forecast-based regime and results in price levels close to the base case with a slightly lower operating cost.

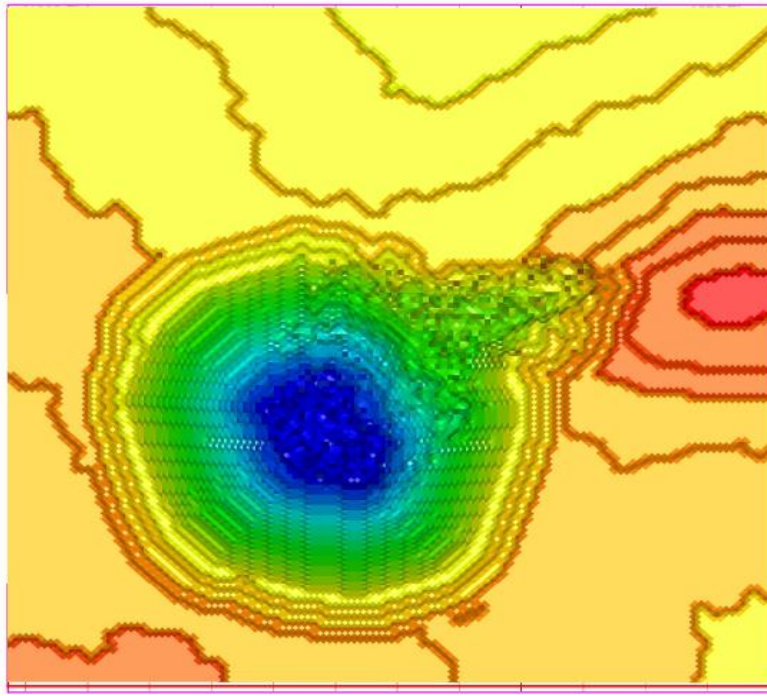
These scenario-specific economic parameters were applied as fixed inputs in the deterministic optimization model implemented in Datamine NPVS. The resulting optimization outcomes for each case are presented in the following section.

4.5 Base case results

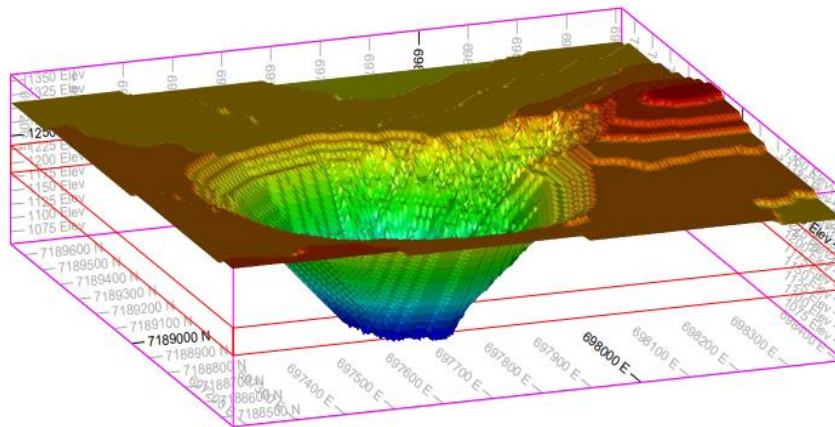
The base case represents the reference economic scenario used for pit optimization, pushback design, and production scheduling of the deposit. The economic block model was evaluated using the Lerchs–Grossmann optimization algorithm to determine the ultimate pit limit under the defined commodity prices, operating costs, and processing assumptions. The resulting optimized pit was subsequently subdivided into mining phases and scheduled in order to define the extraction sequence and the yearly production profile. The economic cut-off grades applied in the base case optimization were defined based on the economic parameters used in the block model evaluation. The calculated economic cut-off grade for gold is 1.1893 g/t, while the economic cut-off grade for copper is 0.19 percent. These cut-off values were used to classify blocks as ore or waste during the pit optimization process and therefore directly influence the distribution of mineable material within the optimized pit. Blocks with grades above these thresholds were considered economically processable, while blocks below the cut-off grades were treated as waste in the optimization and subsequent scheduling calculations.

Ultimate Pit Limit

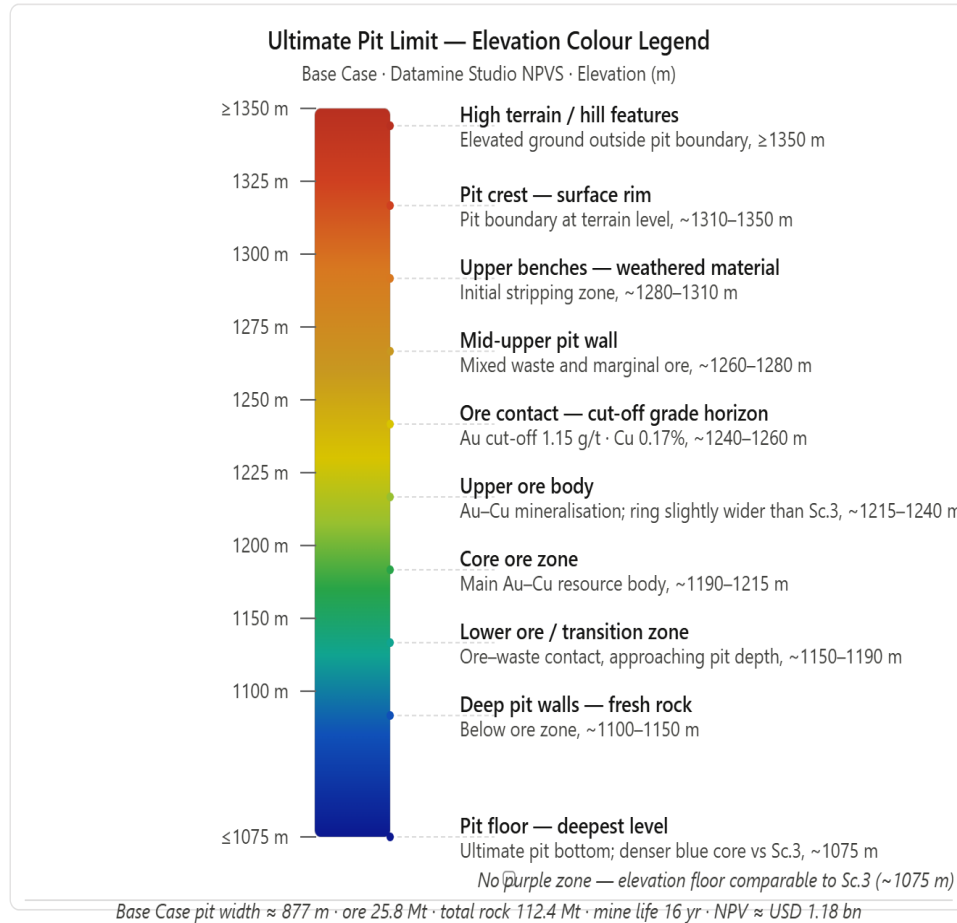
The ultimate pit limit defines the economically optimal boundary of the open pit under the base case economic parameters. The optimization process generated a sequence of nested pit shells corresponding to increasing revenue factors, with the final shell representing the maximum economic extent of the deposit.



(a) Ultimate pit limit, view from top



(b) Ultimate pit limit, view from side



(c) Legend

Figure 4. Ultimate Pit Limit for Base case

The optimized pit contains a total of 112,398,200 tonnes of material. Of this amount, 25,829,700 tonnes correspond to ore while the remaining material represents waste. Waste materials consist of 49,425,200 tonnes of weathered material, 24,550,200 tonnes of soil material, and 241,800 tonnes of fresh waste rock. The geometric characteristics of the optimized pit indicate a lateral extent with an approximate pit width of 877.08 m across the deposit.

The economic evaluation of the ultimate pit indicates a total revenue of 4,449,037,787 USD. The total processing cost associated with the pit is estimated at 434,771,415 USD, while the total mining cost is estimated at 695,107,425 USD. Based on these economic parameters, the optimized pit generates an economic value of approximately 1,179,392,552 USD.

The deposit contained within the optimized pit includes 97,006,803 grams of gold and 51,626 tonnes of copper as contained metals. After applying the recovery parameters defined in the economic model, the recoverable metal quantities are estimated at 51,966,382 grams of gold and 25,474 tonnes of copper. The overall stripping ratio for the optimized pit is approximately 3.35.

Pushback Design

After the ultimate pit limit was determined, the pit was subdivided into mining phases in order to define the sequence of extraction. Pushbacks represent intermediate pit shells that allow progressive expansion of the pit during mining operations while maintaining operational access to deeper ore zones.

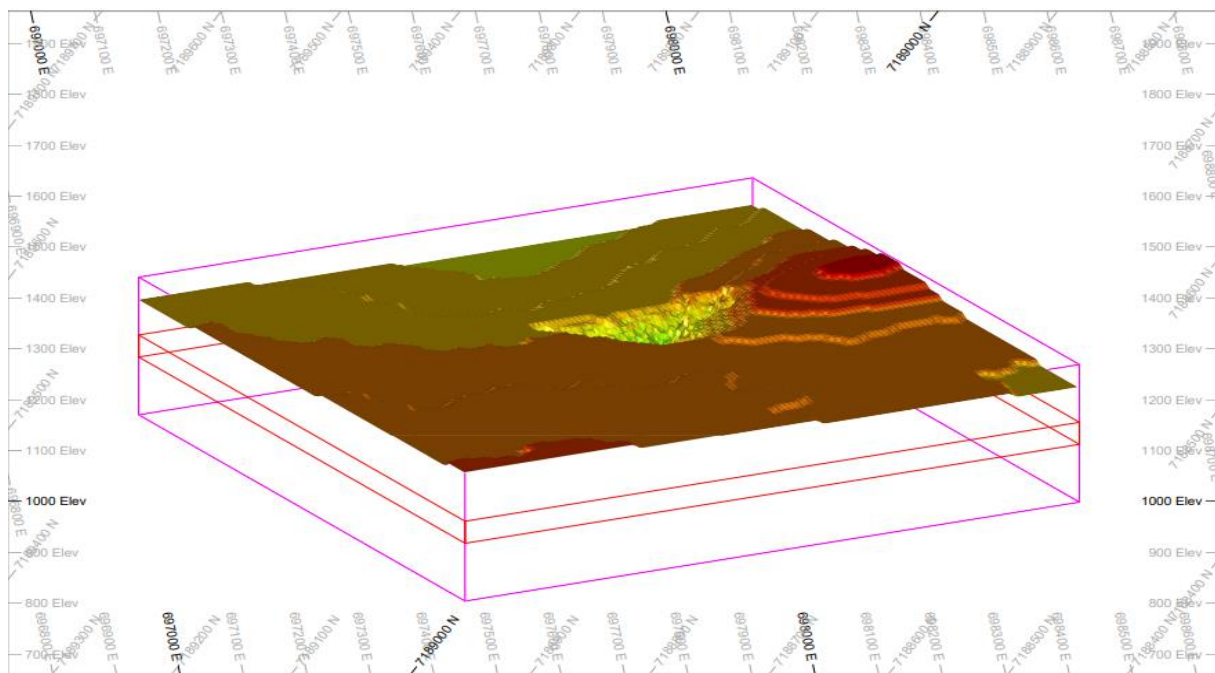


Figure 5. Pushback 1

The first pushback contains approximately 7,340,700 tonnes of material and generates an economic value of 534,873,386 USD. The material extracted within this phase includes 5,140,200 tonnes of ore and associated waste materials located within the upper portion of the deposit.

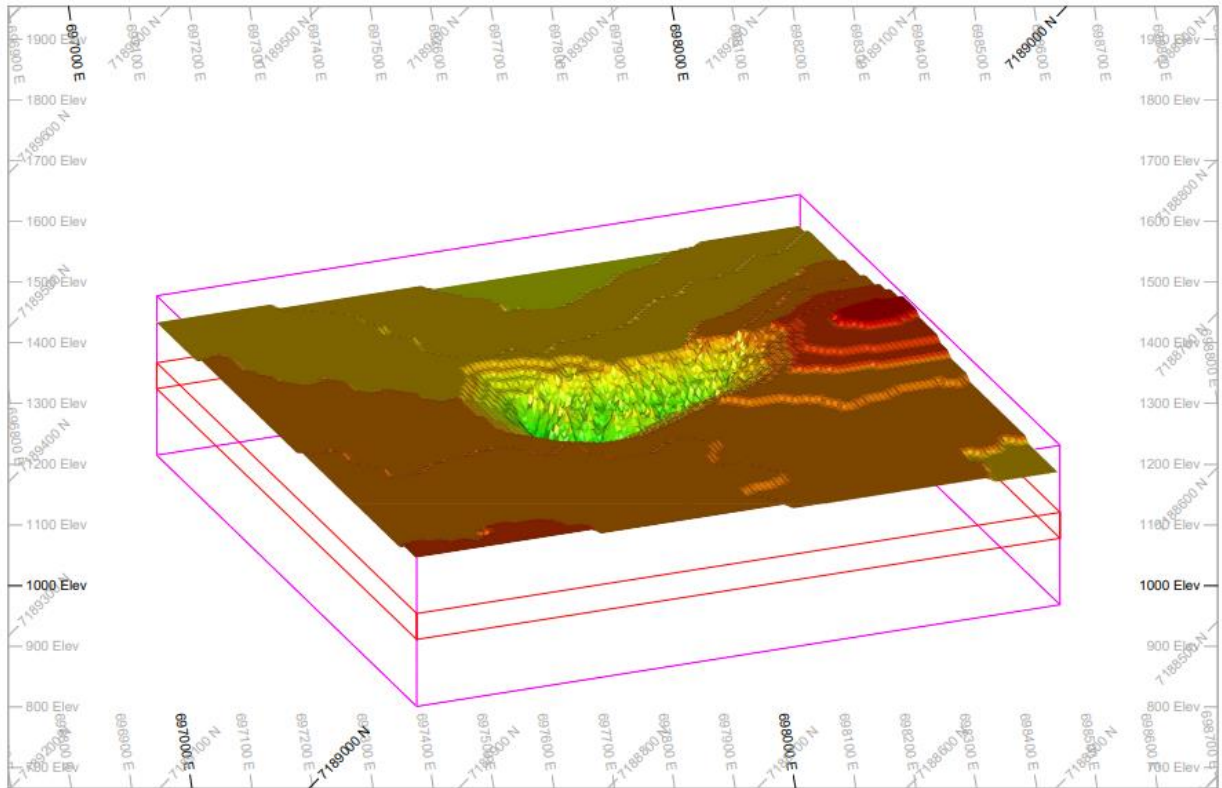


Figure 6. Pushback 2

The second pushback expands the pit boundaries and increases the cumulative material mined to 20,788,800 tonnes. The cumulative economic value associated with the first two pushbacks is estimated at 750,985,555 USD.

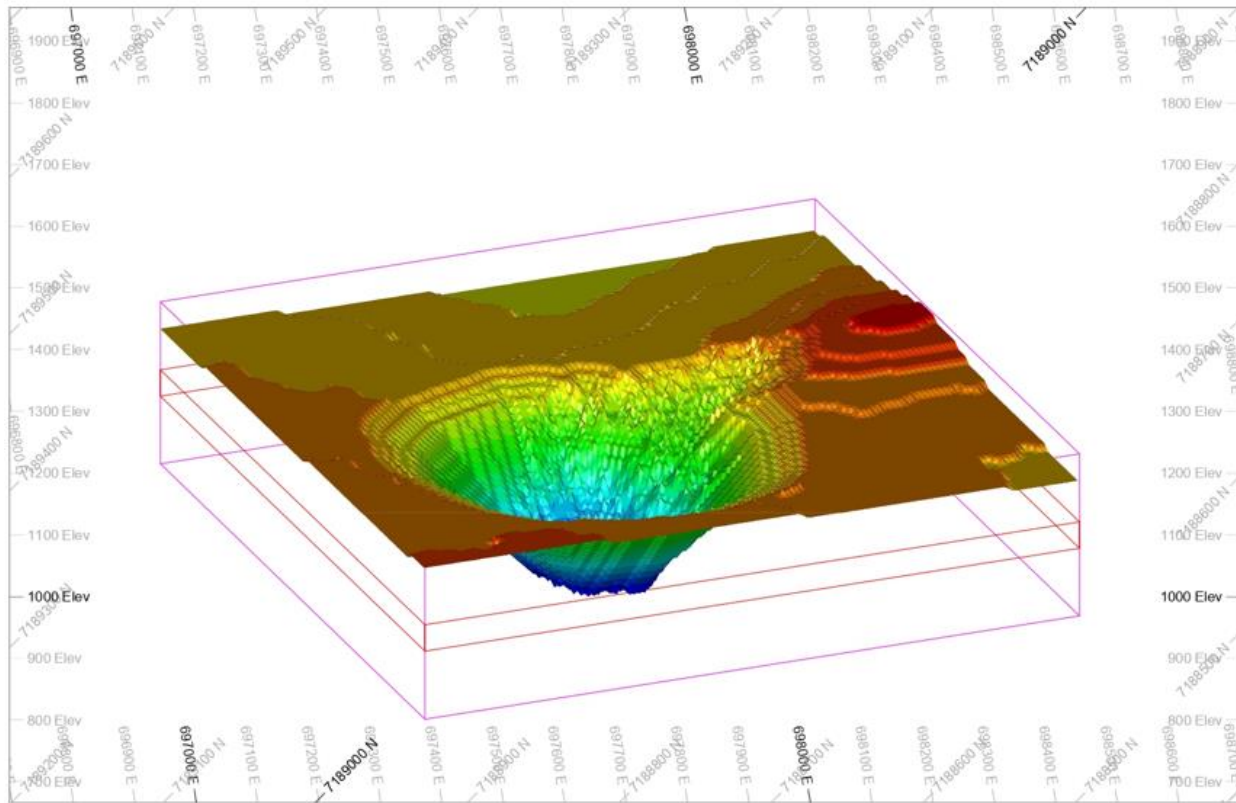


Figure 7. Pushback 3

The final pushback corresponds to the complete ultimate pit and contains a total of 112,398,200 tonnes of material. The cumulative economic value associated with all pushback phases is estimated at 976,116,058 USD. The cumulative ore tonnage within the final pushback is 25,829,700 tonnes.

Production Scheduling

Following the pushback design, a long-term production schedule was generated to define the yearly mining sequence and evaluate the economic performance of the operation. The resulting production schedule indicates a mine life of 16 years.

During the life of the mine, a total of 112,429,900 tonnes of material are mined. The total ore processed during the production period is 25,845,300 tonnes. Waste material removed during the schedule includes 49,429,600 tonnes of weathered material, 24,550,200 tonnes of soil material, and 241,800 tonnes of fresh waste rock.

The total revenue generated during the production period is estimated at 4,449,598,262 USD. The total processing cost is estimated at 435,094,335 USD, while the total mining cost is estimated at 695,338,575 USD. The resulting economic value of the scheduled operation is approximately 1,055,953,207 USD.

The scheduled production contains 97,036,424 grams of gold and 51,650 tonnes of copper as contained metals. The estimated recoverable metal quantities are 51,972,298 grams of gold and 25,483 tonnes of copper.

Base Case Summary

The base case optimization defines the overall economic and operational characteristics of the deposit under the reference economic assumptions. The optimized pit contains approximately 112.40 million tonnes of material and generates a net present value of approximately 1.179 billion USD. The production schedule developed for the optimized pit results in a mine life of 16 years and processes approximately 25.85 million tonnes of ore over the life of the operation.

Table 7. Summary for Base Case Optimization.

Parameter	Value
Total rock mined	112,398,200 t
Total ore mined	25,829,700 t
Total waste mined	86,568,500 t
Stripping ratio	3.35
Mine life	16 years
Revenue	4,449,037,787 USD
Processing cost	434,771,415 USD
Mining cost	695,107,425 USD
Net present value (NPV)	1,179,392,552 USD
Gold contained	97,006,803 g
Copper contained	51,626 t
Gold recovered	51,972,298 g
Copper recovered	25,483 t
Pit width	877.08 m

4.6 Scenario 1 Results

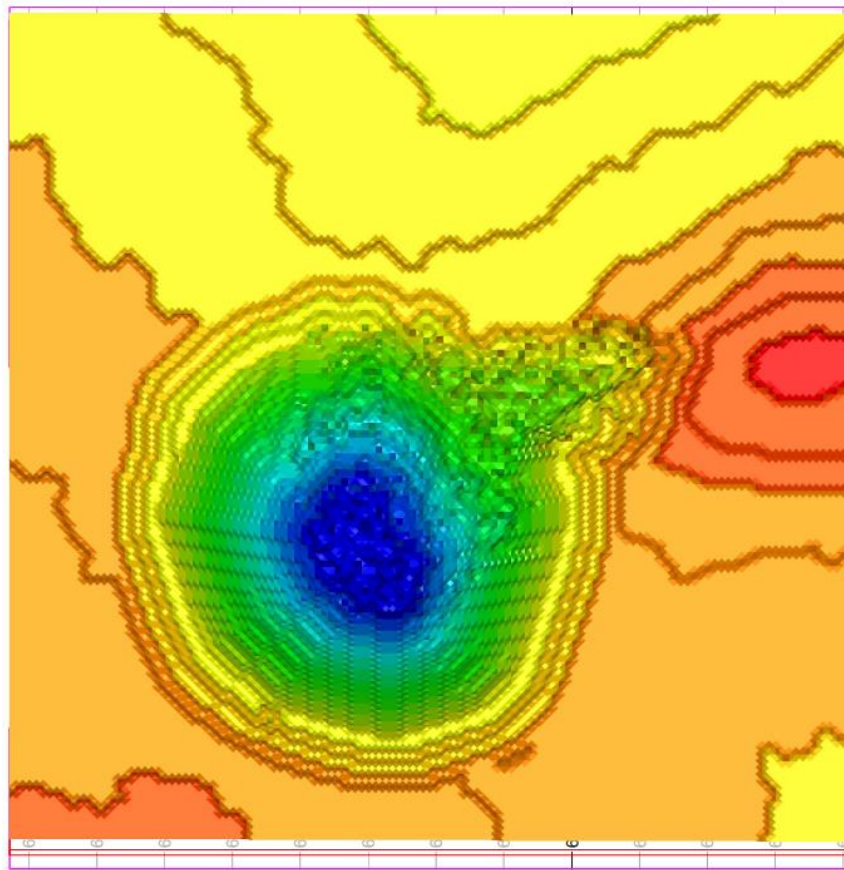
Scenario 1 represents the historical economic conditions corresponding to the period from 1980 to 2000. This scenario is designed to reflect long-term commodity price behavior during earlier market conditions and to evaluate how the project performs under historically observed pricing

levels. The selected parameters include a gold price of 59.64 USD/g and a copper price of 8,477 USD/t, along with an operating cost of 15.3 USD/t.

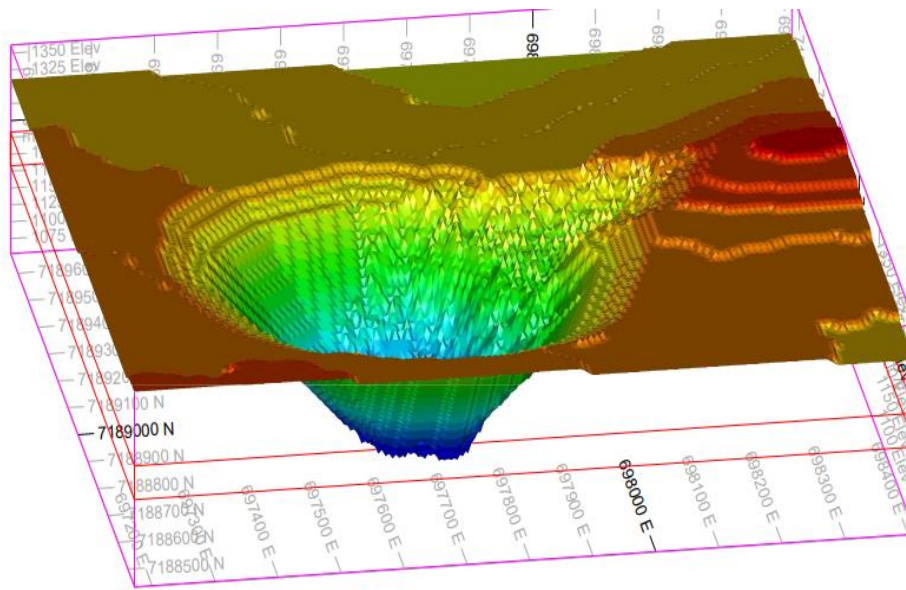
In addition to commodity prices, the economic model incorporates processing and mining parameters that influence the valuation of each block. The processing cost is set at 7.6 USD/t, while mining costs are adjusted based on material type using predefined cost multipliers. Metal recoveries for gold and copper are calculated using grade-dependent recovery functions, allowing for a more realistic representation of processing performance. The cut-off grades are determined using a revenue-based approach, resulting in an economic cut-off grade of 1.3057 g/t for gold and 0.20% for copper. These parameters collectively define whether a block is classified as ore or waste and directly control the economic limits of the pit.

Ultimate Pit Limit

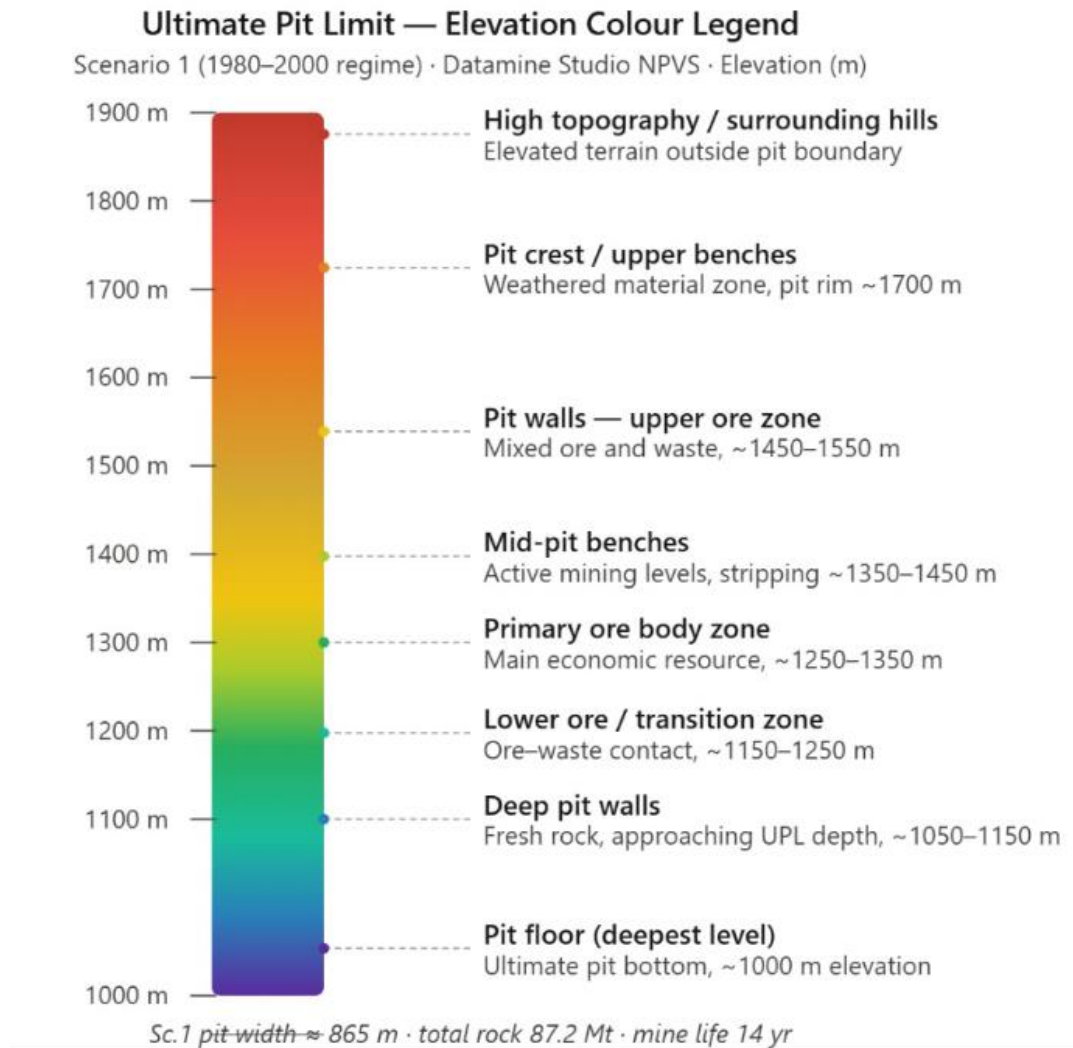
The ultimate pit limit defines the economically optimal boundary of the open pit under the Scenario 1 economic parameters. The optimization generated a sequence of nested pit shells corresponding to increasing revenue factors, with the final selected shell representing the economically optimal extent of the deposit.



(a) Ultimate pit limit, view from the top



(b) Ultimate pit limit, view from side



(d) Legend

Figure 8. UPL for Scenario 1

The optimized pit contains a total of 104,654,200 tonnes of material. Of this amount, approximately 24,063,000 tonnes correspond to ore, while the remaining material represents waste. Waste materials consist primarily of 43,003,400 tonnes of weathered material, 23,167,800 tonnes of soil material, and 341,000 tonnes of fresh waste rock. The geometric characteristics of the optimized pit indicate a lateral extent with an approximate pit width of 865.29 m across the deposit.

The economic evaluation of the ultimate pit indicates a total revenue of approximately 3,089,348,160 USD. The total processing cost associated with the pit is estimated at 393,969,420 USD, while the total mining cost is estimated at 659,447,060 USD. Based on these economic parameters, the optimized pit generates an economic value of approximately 804,272,971 USD. The deposit contained within the optimized pit includes approximately 91,942,408 grams of gold and 48,744 tonnes of copper as contained metals. After applying the recovery parameters defined

in the economic model, the recoverable metal quantities are estimated at approximately 49,686,589 grams of gold and 24,211 tonnes of copper. The overall stripping ratio for the optimized pit is approximately 3.35.

Pushback Design

After the ultimate pit limit was determined, the pit was subdivided into mining phases in order to define the sequence of extraction. Pushbacks represent intermediate pit shells that allow progressive expansion of the pit during mining operations while maintaining operational access to deeper ore zones.

The first pushback entails the early mining operations, where 8.24 million tonnes of the material are expected to be mined with an income of 636.34 million USD. The cost for processing and mining operations amounts to 46.11 million USD and 58.15 million USD, respectively, leading to a net present value of 387.74 million USD. It generates the highest income among all other stages, hence taking preference during the beginning of mining operations.

The second pushback involves 15.05 million tonnes of material, producing an income of 628.05 million USD. The processing and mining costs involved amount to 66.10 million USD and 94.98 million USD, respectively, leading to a net present value of 171.61 million USD. The value generated by this stage is relatively low compared to the first stage but still significant for the whole mining process.

The third pushback stage involves 63.88 million tonnes of material, leading to income of 1.75 billion USD. Despite having more material, the net present value generated is 119.22 million USD due to the high stripping requirement within the deepest level of the pit. The cumulative results of all pushbacks indicate a total material movement of 87.17 Mt and a total NPV of 678.57 million USD. This value is lower than the ultimate pit NPV due to the staged mining approach and the effect of discounting during sequential extraction. Images illustrating the pushback stages are provided in the Appendixes.

Production Scheduling

Following the pushback design, a long-term production schedule was generated to define the yearly mining sequence and evaluate the economic performance of the operation. The resulting production schedule indicates a mine life of 14 years. During the life of the mine, a total of 87,174,200 tonnes of material are mined. The total ore processed during the production period is 23,173,800 tonnes. Waste material removed during the schedule includes approximately 31,884,600 tonnes of weathered material, 19,884,600 tonnes of soil material, and 238,700 tonnes of fresh waste rock.

The total revenue generated during the production period is estimated at 3,015,278,964 USD. The total processing cost is estimated at 372,671,442 USD, while the total mining cost is estimated at 553,519,438 USD. The resulting economic value of the scheduled operation is approximately 717,205,096 USD. The scheduled production contains approximately 89,320,579 grams of gold and 47,029 tonnes of copper as contained metals. The estimated recoverable metal quantities are approximately 48,530,417 grams of gold and 23,384 tonnes of copper.

Scenario 1 Summary

The Scenario 1 optimization defines the economic and operational characteristics of the deposit under the historical economic conditions corresponding to the period 1980–2000. The optimized pit contains approximately 104.65 million tonnes of material and generates a net present value of approximately 804.27 million USD. The production schedule developed for the optimized pit results in a mine life of 14 years and processes approximately 23.17 million tonnes of ore over the life of the operation.

The main economic and operational indicators of Scenario 1 are summarized in table below:

Table 8. Summary for Scenario 1 Optimization

Parameter	Value
Total rock mined	104,654,200 t
Total ore mined	24,063,000 t
Total waste mined	80,591,200 t
Stripping ratio	3.35
Mine life	14 years
Revenue	3,089,348,160 USD
Processing cost	393,969,420 USD
Mining cost	659,447,060 USD
Net present value (NPV)	717,205,096 USD
Gold contained	91,942,408 g
Copper contained	48,744 t
Gold recovered	49,686,589 g
Copper recovered	24,211 t
Pit width	865.29 m

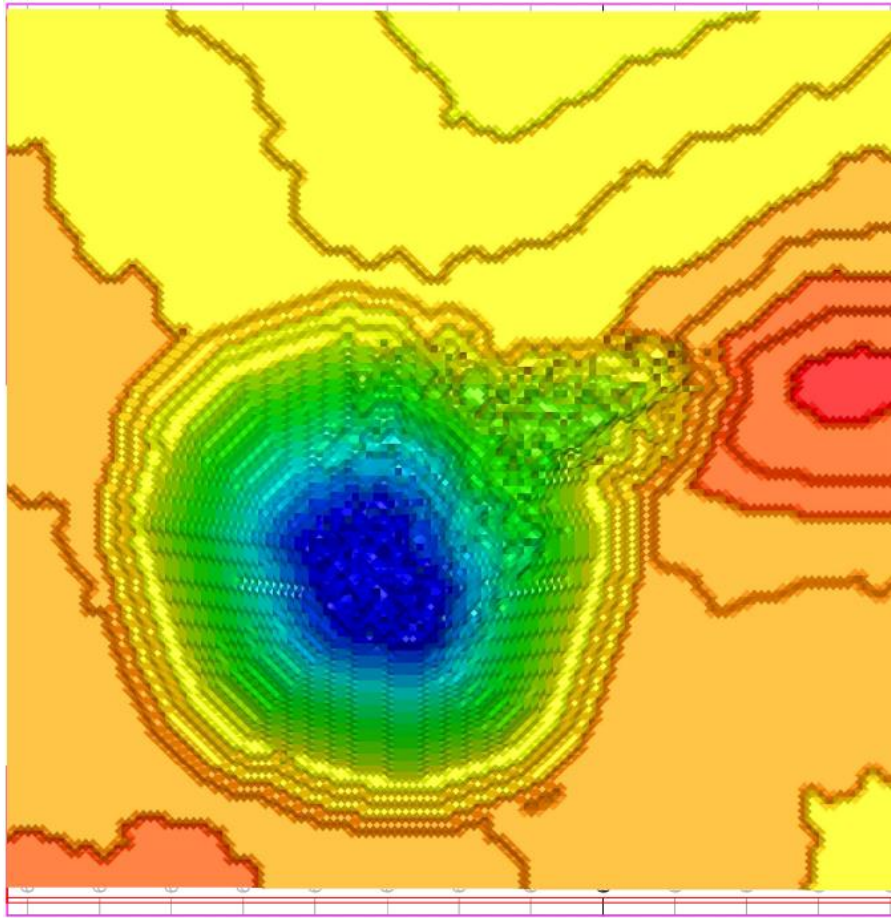
4.7 Scenario 2 Results

Scenario 2 represents the economic conditions corresponding to the period from 2000 to 2024, reflecting the commodity price trends observed during this timeframe. Under this scenario, the block model was evaluated using increased metal prices and operating costs derived from the observed market conditions, resulting in higher revenue potential per block. The optimized pit was subsequently subdivided into mining phases and scheduled to determine the extraction sequence and production profile.

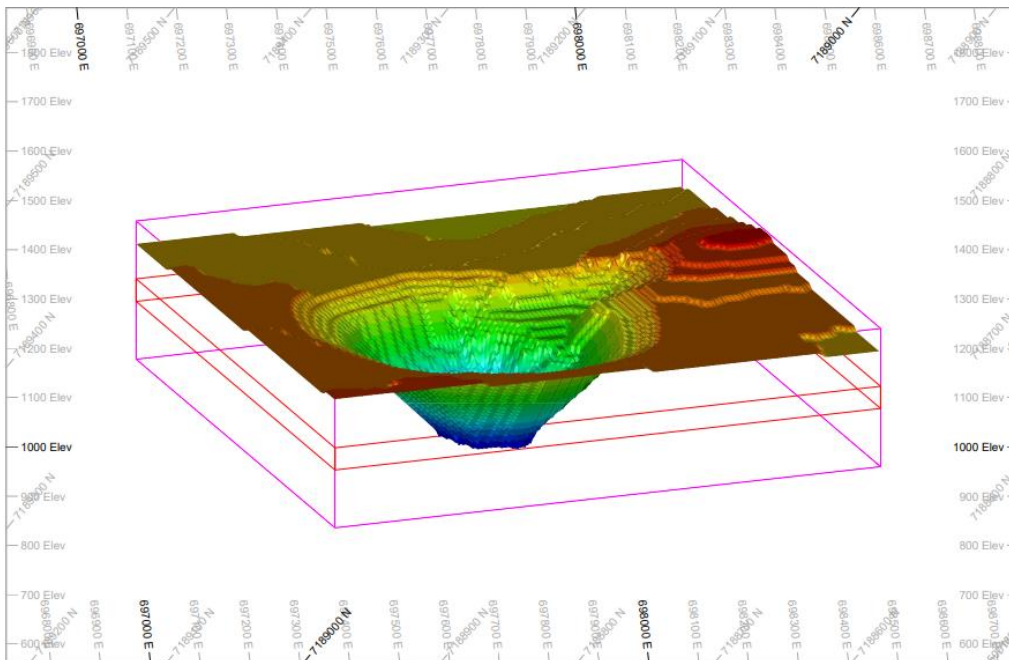
The economic cut-off grades applied in Scenario 2 were derived from the economic parameters defined in the model. The calculated economic cut-off grade for gold is 1.0647 g/t, while the economic cut-off grade for copper is 0.17 percent. These cut-off grades were used to classify blocks as ore or waste during the optimization process and therefore directly influence the distribution of mineable material within the optimized pit. Blocks exceeding these thresholds were treated as economically processable ore, while blocks below these values were considered waste material during the optimization and scheduling calculations.

Ultimate Pit Limit

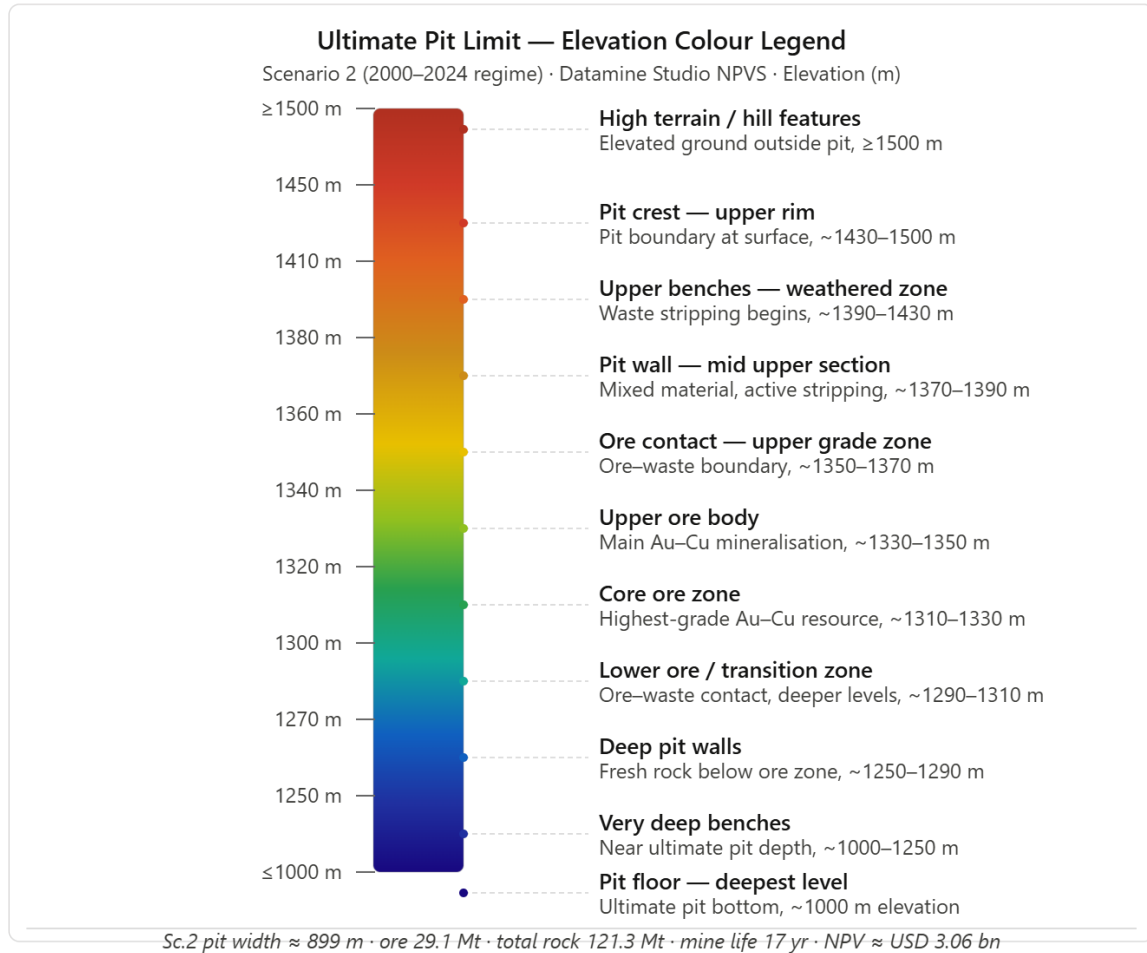
The ultimate pit limit defines the economically optimal boundary of the open pit under the Scenario 2 economic conditions. The optimization process generated a sequence of nested pit shells corresponding to increasing revenue factors, with the final shell representing the maximum economic extent of the deposit.



(a) Ultimate pit limit, view from the top



(b) Ultimate pit limit, view from side



(c) Legend

Figure 9. Ultimate Pit Limit for Scenario 2

The optimized pit contains a total of 130,307,300 tonnes of material. Of this amount, approximately 29,460,600 tonnes correspond to ore, while the remaining material represents waste. Waste materials consist primarily of 61,384,400 tonnes of weathered material, 27,576,000 tonnes of soil material, and 381,300 tonnes of fresh waste rock.

The economic evaluation of the ultimate pit indicates a total revenue of approximately 12,304,971,016 USD. The total processing cost associated with the pit is estimated at 644,327,190 USD, while the total mining cost is estimated at 1,337,261,938 USD. Based on these economic parameters, the optimized pit generates an economic value of approximately 3,287,770,758 USD.

The deposit contained within the optimized pit includes approximately 102,084,281 grams of gold and 58,552 tonnes of copper as contained metals. After applying the recovery parameters defined in the economic model, the recoverable metal quantities are estimated at approximately 53,210,963 grams of gold and 28,760 tonnes of copper. The overall stripping ratio for the optimized pit is approximately 3.42

Pushback Design

After the ultimate pit limit was determined, the pit was subdivided into mining phases in order to define the sequence of extraction. Pushbacks represent intermediate pit shells that allow progressive expansion of the pit during mining operations while maintaining operational access to deeper ore zones. Illustrations of the pushback stages are provided in the Appendixes.

The first pushback contains approximately 6,998,100 tonnes of material and generates an economic value of 1,487,067,684 USD. The material extracted within this phase includes 5,249,400 tonnes of ore located within the upper portion of the deposit.

The second pushback expands the pit boundaries and increases the cumulative material mined to 21,398,500 tonnes. The cumulative economic value associated with the first two pushbacks is estimated at 2,145,740,329 USD.

The final pushback corresponds to the complete ultimate pit and contains a total of 121,288,800 tonnes of material. The cumulative economic value associated with all pushback phases is estimated at 2,777,519,777 USD. The cumulative ore tonnage within the final pushback is 29,121,300 tonnes. All the pushback images are illustrated in Appendix

Production Scheduling

Following the pushback design, a long-term production schedule was generated to define the yearly mining sequence and evaluate the economic performance of the operation. The resulting production schedule indicates a mine life of 17 years.

During the life of the mine, a total of 121,288,800 tonnes of material are mined. The total ore processed during the production period is 29,121,300 tonnes. Waste material removed during the schedule includes 55,644,600 tonnes of weathered material, 26,064,000 tonnes of soil material, and 260,400 tonnes of fresh waste rock.

The total revenue generated during the production period is estimated at 12,269,311,866 USD. The total processing cost is estimated at 635,013,405 USD, while the total mining cost is estimated at 1,246,515,750 USD. The resulting economic value of the scheduled operation is approximately 3,059,309,135 USD.

The scheduled production contains 101,567,897 grams of gold and 57,942 tonnes of copper as contained metals. The estimated recoverable metal quantities are 53,075,330 grams of gold and 28,469 tonnes of copper.

Scenario 2 Summary

The Scenario 2 optimization defines the economic and operational characteristics of the deposit under the commodity price conditions observed during the 2000–2024 period. The optimized pit contains approximately 121.29 million tonnes of material and generates a net present value of approximately 3.06 billion USD. The production schedule developed for the optimized pit results in a mine life of 17 years and processes approximately 29.12 million tonnes of ore over the life of the operation.

Table 9. Summary for Scenario 2 Optimization.

Parameter	Value
Total rock mined	121,288,800 t
Total ore mined	29,121,300 t
Total waste mined	92,167,500 t
Stripping ratio	3.16
Mine life	17 years
Revenue	12,269,311,866 USD
Processing cost	635,013,405 USD
Mining cost	1,246,515,750 USD
Net present value (NPV)	3,059,309,135 USD
Gold contained	101,567,897 g
Copper contained	57,942 t

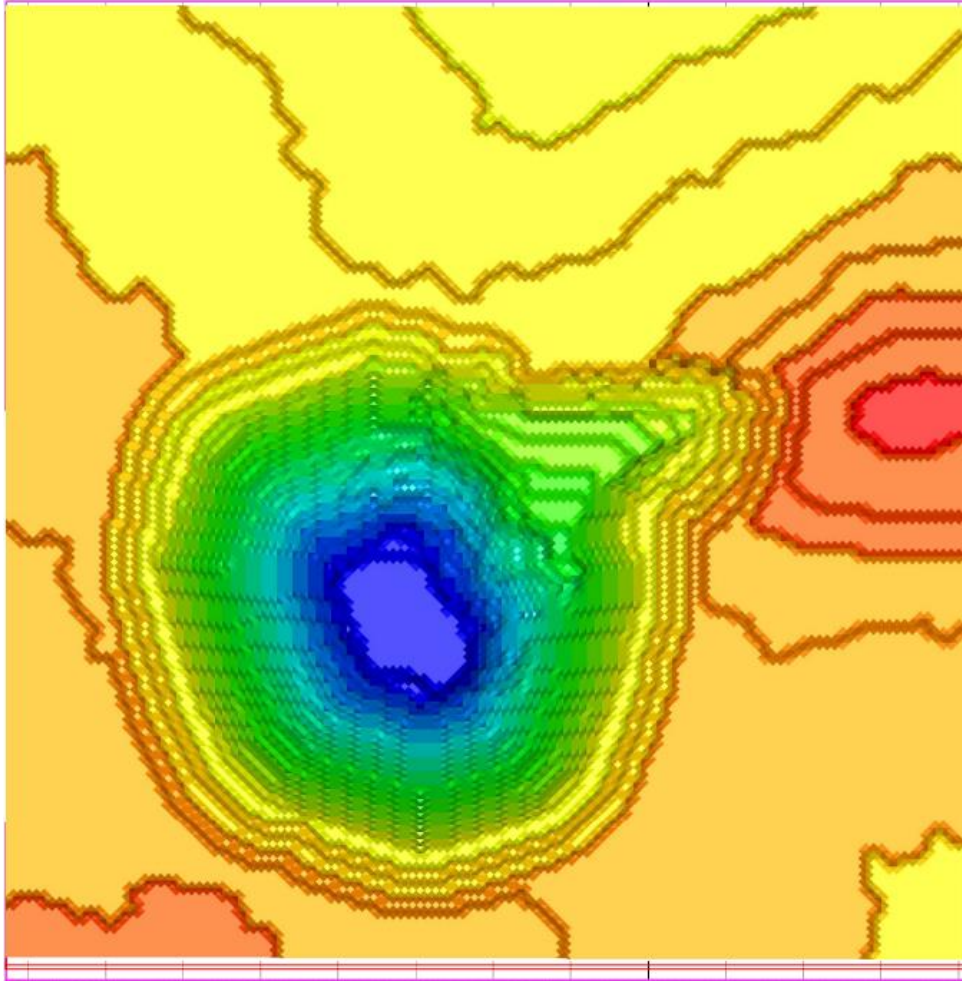
Gold recovered	53,075,330 g
Copper recovered	28,469 t
Pit width	899 m

4.8 Scenario 3 Results

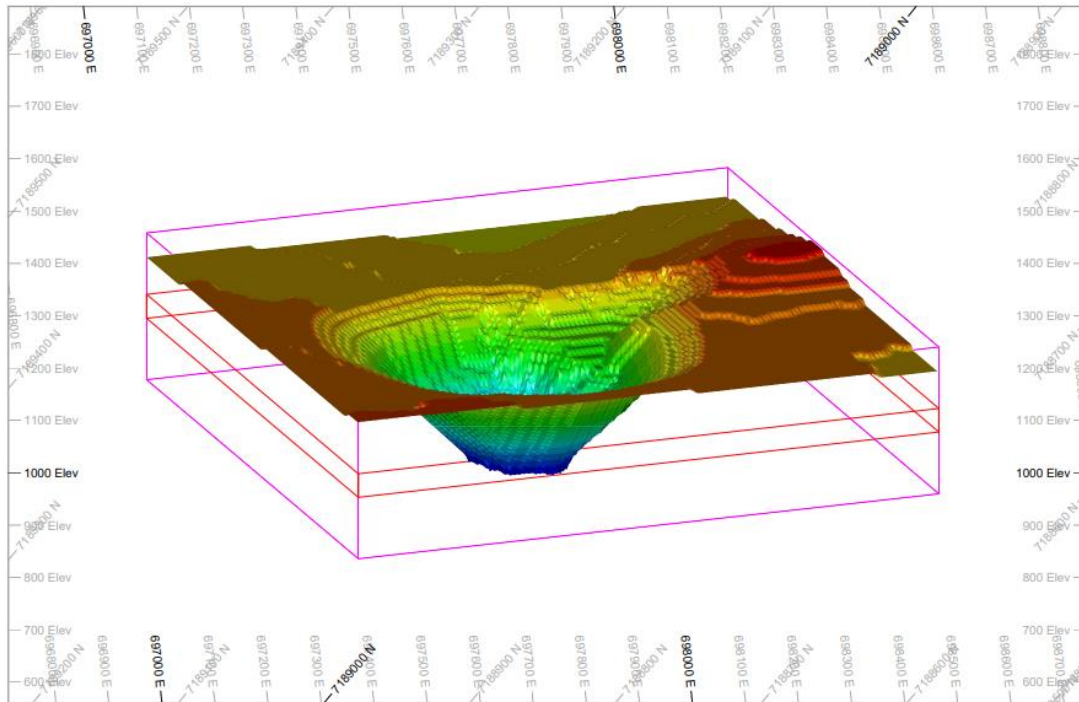
Scenario 3 represents forecast based economic regime, using average price in the span 2023-2025. The selected parameters include a gold price of 81.76 USD/g and a copper price of 10,494 USD/t, along with an operating cost of 13.00 USD/t. In addition to commodity prices, the economic model incorporates processing and mining parameters that influence block valuation. The processing cost is set at 6.5 USD/t, while mining costs are adjusted using material-dependent multipliers. Metal recoveries for gold and copper are calculated using grade-dependent recovery functions. The economic cut-off grades are determined using a revenue-based approach, resulting in a cut-off grade of 1.1536 g/t for gold and 0.17 percent for copper. These parameters define the classification of blocks as ore or waste and directly control the economic limits of the optimized pit.

Ultimate Pit Limit

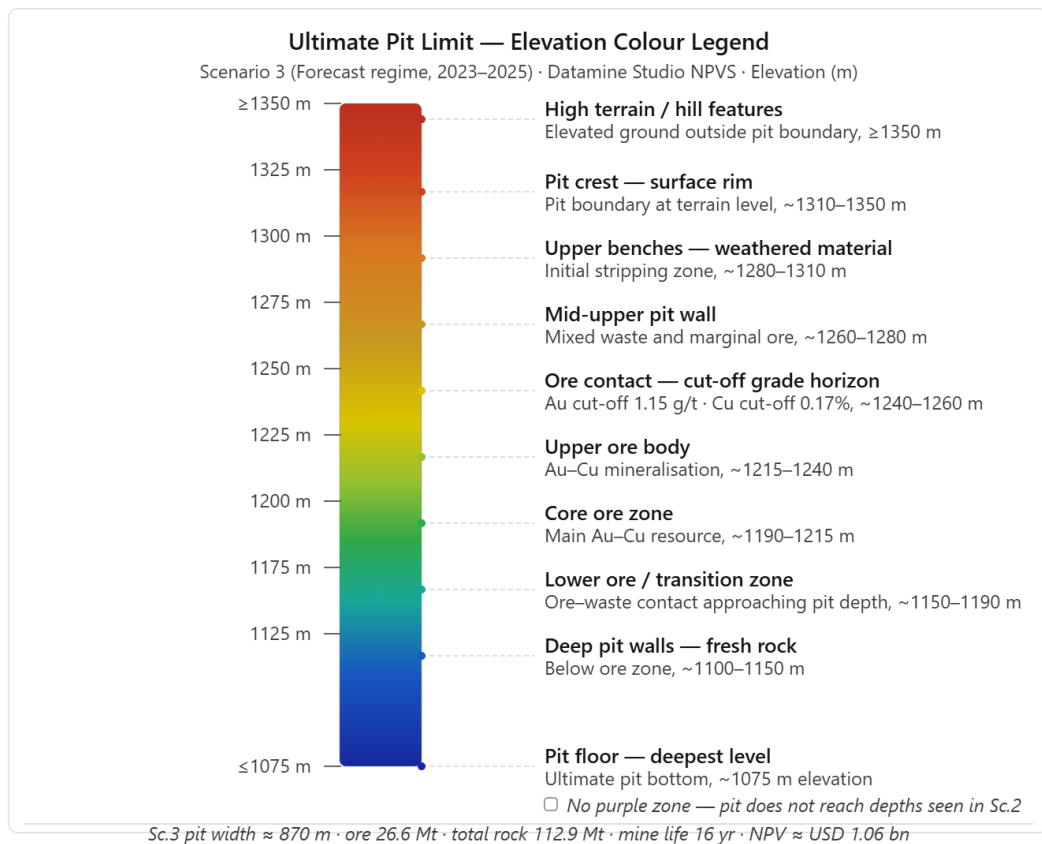
The pit optimization generated a sequence of nested pit shells across revenue factors ranging from 2% to 100%. The ultimate pit limit corresponds to the pit shell generated at the highest revenue factor, which provides the maximum economic value under the applied economic conditions. The resulting optimized pit has an approximate width of 870 m.



(a) Ultimate pit limit, view from top



(b) Ultimate pit limit, view from side



(c) Legend

Figure 10. UPL for Scenario 3.

The optimized pit contains approximately 122,335,600 tonnes of total rock. Within this volume, approximately 26,949,000 tonnes correspond to ore material, while the remaining material represents waste. The total revenue generated from the optimized pit reaches approximately 4,447,504,116 USD. The associated processing and mining costs amount to approximately 431,923,050 USD and 654,617,958 USD respectively. Under these conditions, the resulting net present value reaches approximately 1,170,355,106 USD.

The optimized pit also contains approximately 98,450,368 g of gold and 54,361 tonnes of copper. After applying metallurgical recovery factors, the recoverable metal quantities are estimated at approximately 52,336,540 g of gold and 26,921 tonnes of copper.

Pushback Design

Based on the ultimate pit geometry, a phased mining strategy consisting of three pushbacks was developed to support practical mine development and sequencing. The pushback design allows for the gradual expansion of the pit while maintaining operational feasibility and progressive access to ore zones. Visual representations of the pushback stages are provided in the Appendixes.

The first pushback contains approximately 6,823,800 tonnes of rock, including about 5,050,500 tonnes of ore. This stage generates approximately 791,550,891 USD in revenue with a resulting NPV of approximately 524,619,623 USD.

The second pushback expands the mining area to approximately 19,624,600 tonnes of rock and includes about 9,449,700 tonnes of ore. This stage generates approximately 1,451,307,095 USD in revenue and produces an NPV of approximately 744,584,537 USD.

The final pushback corresponds to the complete ultimate pit limit and includes approximately 112,864,300 tonnes of rock and 26,570,700 tonnes of ore. This phase generates total revenue of approximately 4,421,113,444 USD and produces an NPV of approximately 975,271,820 USD.

Production Scheduling

Following the pushback design, a production schedule was developed to distribute mining activities across the life of mine. The resulting schedule spans sixteen years and defines the annual extraction of rock and ore to ensure continuous processing and stable operational conditions.

Mining begins at a relatively small scale during the initial years, with approximately 814,500 tonnes of rock mined in the first year and 503,100 tonnes of ore processed. As pit development progresses and deeper ore zones become accessible, production rates increase significantly.

By the middle of the mine life, annual rock extraction reaches approximately 67–76 million tonnes, reflecting the period of maximum stripping activity and full production capacity. During these years, large volumes of waste are removed to maintain access to deeper ore zones.

Toward the final years of the schedule, mining activity gradually decreases as the ultimate pit limits are reached. By the final year, cumulative mining reaches approximately 112,864,300 tonnes of rock and 26,570,700 tonnes of ore.

Across the entire schedule, the project generates cumulative revenue of approximately 4,421,113,444 USD with associated processing and mining costs of approximately 423,735,975 USD and 604,962,670 USD respectively. The total net present value produced by the production schedule is approximately 1,059,353,924 USD. The strip ratio evolves throughout the mine life, increasing during the mid-life stripping phase and declining toward the end of the operation as ore extraction dominates.

Table 10. Scenario 3 Optimization results.

Summary of Scenario 3 Results

Parameter	Value
Total rock mined	112,864,300 t
Total ore mined	26,570,700 t
Total waste mined	86,293,600 t
Stripping ratio	3.25
Mine life	16 years
Revenue	4,421,113,444 USD

Processing cost	423,735,975 USD
Mining cost	604,962,670 USD
Net present value (NPV)	1,059,353,924 USD
Gold contained	97,672,427 g
Copper contained	53,552 t
Gold recovered	52,058,410 g
Copper recovered	26,508 t
Pit width	870 m

5. Discussion

5.1 Comparative Analysis of Optimization Results

A comparative analysis of the optimization outcomes was conducted in order to evaluate the differences between the base case and the three economic scenarios. The results obtained from the deterministic optimization model are summarized in Table 11. The table consolidates the main operational and economic indicators reported in Chapter 4 and provides a basis for examining how variations in commodity price regimes and operating costs influenced the resulting pit configurations and project valuation.

The variation in optimization outcomes across the evaluated scenarios can be explained by the direct influence of economic parameters on block valuation within the Lerchs–Grossmann framework. An increase in commodity prices raises the economic value assigned to individual blocks, which shifts marginal material from waste to ore classification and results in an expansion of the ultimate pit limit. This expansion increases the total recoverable ore tonnage and extends mine life, ultimately contributing to higher net present value. Conversely, lower price regimes reduce block profitability, leading to contraction of the pit boundary and a decrease in economically recoverable material. The results obtained in this study therefore confirm that pit optimization is highly sensitive to economic inputs, and that even moderate variations in price assumptions can produce significant changes in both geometric and financial outcomes of the mining project.

Table 11. Summary of optimization results for all economic scenarios

Parameter	Base Case	Scenario 1	Scenario 2	Scenario 3
Total rock mined (t)	112,398,200	87,174,200	121,288,800	112,864,300
Ore mined (t)	25,829,700	23,173,800	29,121,300	26,570,700
Waste mined (t)	86,568,500	64,000,400	92,167,500	86,293,600
Stripping ratio	3.35	2.76	3.16	3.25
Mine life (years)	16	14	17	16
Revenue (USD)	4,449,037,787	3,015,278,964	12,269,311,866	4,421,113,444
Processing cost (USD)	434,771,415	372,671,442	635,013,405	423,735,975
Mining cost (USD)	695,107,425	553,519,438	1,246,515,750	604,962,670
Net present value (USD)	1,179,392,552	717,205,096	3,059,309,135	1,059,353,924
Gold contained (g)	97,006,803	89,320,579	101,567,897	97,672,427

Copper contained (t)	51,626	47,029	57,942	53,552
Annual production(t/year)	1,614,356	1,655,271	1,713,018	1,660,669

5.2 Economic Interpretation of Optimization Outcomes

The base case represents the reference economic environment derived from recent commodity price averages. In this case, the optimized pit contains 112,398,200 tonnes of total rock and 25,829,700 tonnes of ore, with a stripping ratio of 3.35. The geometry of the optimized pit corresponds to an approximate pit width of 877.08 m. The production schedule developed for this pit results in a mine life of sixteen years. Under these economic conditions, the project generates total revenue of 4,449,037,787 USD, while processing and mining costs are estimated at 434,771,415 USD and 695,107,425 USD respectively. These financial outcomes produce a net present value of 1,179,392,552 USD, which provides the reference benchmark for evaluating the alternative economic regimes.

Scenario 1 represents the lowest commodity price environment among the evaluated cases. The lower gold and copper prices applied in this scenario reduce the economic value of blocks within the model and therefore restrict the quantity of material that satisfies the economic criteria for inclusion in the optimized pit. As a result, the total rock mined decreases to 87,174,200 tonnes and the ore tonnage decreases to 23,173,800 tonnes. The optimized pit also shows a lower stripping ratio of 2.76 and a slightly smaller pit width of approximately 865.29 m. The production schedule generated for this pit results in a mine life of fourteen years, which is shorter than the mine life obtained in the other evaluated cases. These operational outcomes correspond with lower contained metal quantities of 89,320,579 grams of gold and 47,029 tonnes of copper. Under these economic conditions, the total revenue decreases to 3,015,278,964 USD and the resulting net present value decreases to 717,205,096 USD.

Scenario 2 represents the strongest commodity price environment among the evaluated cases. Higher gold and copper prices increase the revenue contribution of individual blocks and therefore allow additional blocks to generate positive economic value within the optimization model. This effect expands the economic boundary of the pit and increases the quantity of economically recoverable material. The optimized pit contains 121,288,800 tonnes of total rock and 29,121,300

tonnes of ore, which is the highest ore tonnage among the evaluated scenarios. The stripping ratio for this case is 3.16 and the optimized pit width increases to approximately 899 m, indicating a wider economic extent of the pit. The production schedule results in a mine life of seventeen years, slightly longer than the base case. The optimized pit contains 101,567,897 grams of gold and 57,942 tonnes of copper, which are the highest contained metal quantities among the scenarios. The larger volume of mined and processed material increases both revenue and operating costs, with total revenue reaching 12,269,311,866 USD and processing and mining costs estimated at 635,013,405 USD and 1,246,515,750 USD respectively. Despite the higher costs associated with the larger mining operation, the increased metal revenue results in the highest net present value obtained in the analysis, estimated at 3,059,309,135 USD.

Scenario 3 uses the forecast-based regime and produced results close to those observed in the base case. The optimized pit under this scenario contains 112,864,300 tonnes of total rock and 26,570,700 tonnes of ore. The stripping ratio is estimated at 3.25 and the resulting pit width is approximately 870 m. The production schedule indicates a mine life of sixteen years, consistent with the base case and Scenario 2. The optimized pit contains 97,672,427 grams of gold and 53,552 tonnes of copper as contained metals. Under these economic conditions, total revenue is estimated at 4,421,113,444 USD, while processing and mining costs are calculated at 423,735,975 USD and 604,962,670 USD respectively. These economic conditions produce a net present value of 1,059,353,924 USD.

The comparison of these results demonstrates that variations in the economic inputs applied within the deterministic optimization framework influence the economic boundary of the deposit and the financial performance of the project. Lower commodity price environments reduce the quantity of material classified as economically recoverable and therefore produce smaller pit limits, lower metal production, and reduced project value. In contrast, higher commodity price environments expand the economic extent of the pit by allowing additional blocks to generate positive economic value, which increases the volume of recoverable ore and results in higher project valuation.

Relative to the base case, Scenario 1 shows the largest contraction in operational and economic indicators. The total rock mined decreases by approximately 22.4%, ore mined by 10.3%, and waste mined by 26.1%, with a decline in stripping ratio of 17.6%. This is accompanied by a 32.2% decline in revenue and a 39.2% decline in NPV, along with a decrease in contained gold by 7.9%

and copper by 8.9%.

Scenario 2 shows the highest economic performance. In this case, total rock mined increases by approximately 7.9% and ore mined increases by 12.7%. The revenue increases significantly by 175.8%. Along with increases in processing cost by 46.1% and mining cost by 79.3%, NPV increases by 159.4%, which is the highest among all scenarios.

Scenario 3 remains close to the base case in terms of operational parameters, with total rock mined increasing by approximately 0.4% and ore mined increasing by 2.9%, while the stripping ratio decreases by 3.0%. The revenue shows a slight decrease of 0.6%, accompanied by a reduction in processing cost by 2.5% and mining cost by 13.0%. This results in a decline in NPV by approximately 10.2%.

Overall, NPV demonstrates the highest relative change in response to varying economic conditions, indicating strong sensitivity to fluctuations in commodity prices and cost parameters within the deterministic optimization framework.

The regression analysis conducted in this study reveals varying levels of correlation between commodity prices and time across different periods. Gold prices exhibit relatively strong linear relationships, as indicated by higher coefficients of determination, suggesting a consistent directional trend within the analyzed intervals. In contrast, copper and oil prices demonstrate weaker linear relationships in certain periods, reflected in lower R^2 values, which indicates that time alone does not fully explain their variability. This behavior is consistent with the inherently volatile and cyclical nature of commodity markets, where prices are influenced by multiple external factors such as global demand, geopolitical conditions, and macroeconomic fluctuations. Moreover, it is evident from a careful examination of the regression plots that some price data sets have non-linear patterns. Although more sophisticated models can be used to achieve a better fit, this is not the objective of regression analysis in this paper since it aims at identifying the general trend direction rather than constructing predictive models of commodity prices.

Despite its limitations, the regression analysis serves its intended purpose by confirming the presence of distinct trend behaviors across the defined regimes. Periods characterized by positive trends correspond to higher adjusted commodity prices and improved optimization outcomes, while periods with weaker or negative trends align with reduced economic performance. This demonstrates that the regression-based characterization of commodity price behavior is directly

reflected in the scenario-based optimization results and supports the overall methodological framework of the study

The observed sensitivity of optimization outcomes to economic inputs in this study supports the conclusions of Madziwa et al. (2025), who reported substantial deviations in project valuation under different price assumptions. Although the present study applies static scenario-based adjustments rather than dynamic price modeling, both approaches demonstrate that deterministic optimization results are highly dependent on the economic parameters embedded in the model.

5.3 Implications for Deterministic Mine Planning

While there are evident dependencies between economic scenarios and the optimal outcomes, certain constraints are associated with the deterministic nature of the simulation. First, static price changes do not reflect the temporal variation of prices in commodity markets and can thus have some impact on the optimal pit design. Additionally, the inclusion of the oil price as an independent variable neglects other important cost factors, such as labor costs, equipment costs, and inflation rates. Nevertheless, the research offers several significant insights into mine planning practice. It shows that the use of one set of economic assumptions in the course of optimization can be disadvantageous for the assessment of mining projects. This way, the integration of the scenario-based economic values into the optimization process can ensure the achievement of more realistic outcomes.

Net present value is the central indicator used to evaluate the economic viability of mining projects and represents the primary objective function within the deterministic optimization framework applied in this study. Because the ultimate pit limit is selected based on the maximization of discounted economic value, the NPV obtained in each scenario reflects the overall economic performance of the mine plan generated under the corresponding economic regime. Consequently, the variation in NPV observed between the evaluated scenarios provides an important basis for interpreting how different economic environments influence strategic mine planning outcomes.

The comparison of the evaluated scenarios shows that the project value varies across the different economic regimes. The base case produces an NPV of approximately 1.18 billion USD, while Scenario 1 results in a lower project value and Scenario 2 generates the highest NPV among the

evaluated cases. Scenario 3 produces a project value close to that of the base case. These differences indicate that the financial performance of the optimized mine plan changes when the economic parameters used in the block valuation process are modified. Because the optimization procedure selects the pit configuration that maximizes discounted economic return, any change in the economic value assigned to blocks affects the quantity of material included in the final pit and therefore influences the overall project valuation.

From a mine planning perspective, this result highlights the importance of evaluating alternative economic environments during the planning stage. Deterministic optimization models rely on predefined economic inputs, meaning that the resulting pit configuration represents the optimal solution only for the specific economic conditions assumed in the model. The scenario-based approach applied in this study allows planners to observe how the project value responds when alternative economic regimes are considered. This type of evaluation provides an additional level of insight during strategic planning, because it allows decision makers to assess whether a mine plan remains economically attractive under different commodity price conditions.

The results also demonstrate that the economic regime applied in the optimization process influences the relative attractiveness of the project when evaluated using NPV. When commodity prices are lower, the economic value of marginal blocks decreases and the resulting mine plan generates a lower discounted economic return. Conversely, when commodity prices increase, more blocks generate positive economic value, which expands the economic boundary of the pit and increases the overall project value. The resulting change in NPV therefore reflects the sensitivity of deterministic mine planning outcomes to the economic assumptions used during optimization.

These findings contribute to addressing the research gap identified in the literature review. Previous studies have shown that conventional open pit optimization relies on deterministic economic inputs, even though commodity prices and operating costs may vary significantly over time. While sensitivity analysis is commonly used to examine how economic parameters influence financial outcomes, such analyses are often performed after the pit design has already been determined. The approach applied in this study incorporates alternative economic regimes directly within the optimization process by modifying the economic parameters used for block valuation.

As a result, the differences in NPV observed across the evaluated scenarios provide a practical demonstration of how variations in economic conditions influence the resulting pit configuration and project valuation within a deterministic planning framework.

From a practical perspective, such an approach can be seen to offer mine planners a systematic approach to assessing the robustness of project valuation results using different sets of economic assumptions. In other words, through the assessment of different NPV results using different sets of economic assumptions, mine planners can gain a deeper insight into the dependency of the project's economic performance on the price and cost conditions used in the model.

6. Conclusions and recommendations

6.1 Conclusions

This study investigated the influence of different economic environments on open-pit optimization outcomes within a deterministic mine planning framework. The research focused on evaluating how variations in commodity price regimes and operating costs affect pit configuration, operational indicators, and project valuation when applied directly within the optimization process. The analysis was conducted using a gold–copper block model implemented in Datamine Studio NPVS, where economic parameters were adjusted according to historical and forecast commodity price growth rates.

The results demonstrate that economic parameters play a significant role in determining the outcomes of deterministic open-pit optimization. The reason for this is that the economic value of each block is determined by the prices of the commodities and the costs of operation. Consequently, the configuration of the optimized pit, the amount of material extracted, and the financial results of the mining operation are affected by the changing parameters. The results obtained in this study demonstrate that the aim and objectives of the research were successfully achieved. Historical commodity price data for gold, copper, and oil were analyzed and used to determine average annual growth rates for different economic regimes. These growth rates were subsequently used to construct economic scenarios, which were implemented in a deterministic open-pit optimization model using Datamine Studio NPVS. The resulting optimization outputs were compared across scenarios using operational and economic indicators such as pit size, ore tonnage, stripping ratio, mine life, and net present value. This comparative analysis allowed the influence of alternative economic environments on deterministic pit optimization outcomes to be systematically evaluated.

The comparative analysis of the evaluated scenarios shows that the economic regime derived from the period 2001–2024 produced the highest project value among all cases. Under this scenario, the optimized pit contained approximately 112.56 million tonnes of total rock and 26.27 million tonnes of ore, generating a net present value of approximately 1.31 billion USD. The higher commodity prices applied in this scenario increased the economic value of marginal blocks within

the block model, which expanded the economic boundary of the pit and increased the quantity of economically recoverable material.

In contrast, the historical regime corresponding to the period 1980–2000 produced the lowest project valuation. Under this scenario, lower commodity prices reduced the economic value of blocks within the model, which restricted the extent of the optimized pit. The total rock mined decreased to approximately 104.77 million tonnes and the resulting net present value decreased to approximately 1.13 billion USD. This reduction in pit size and project value demonstrates how unfavorable economic conditions can limit the amount of material that satisfies economic extraction criteria.

The forecast-based economic scenario produced optimization results that were similar to the base case. The optimized pit under this regime contained approximately 112.78 million tonnes of total rock and generated a net present value of approximately 1.18 billion USD. These results indicate that moderate variations in economic parameters may produce relatively small changes in optimization outcomes when compared with more significant shifts in commodity price environments.

Overall, the results validate that deterministic open-pit optimization is sensitive to the underlying economics used in the valuation of the block model. The price regimes used in the valuation of the commodity have an effect on the economic boundary of the deposit, thus impacting the amount of available ore, the mining operation, and the financial performance of the operation. Among the evaluated indicators, net present value exhibited the largest relative variation across scenarios, indicating that project valuation is particularly responsive to changes in economic inputs within deterministic mine planning models.

The methodological approach applied in this study contributes to addressing the research gap identified in the literature. Conventional optimization workflows often apply deterministic economic inputs while economic sensitivity analysis is performed separately from the optimization process. In this research, alternative economic regimes were incorporated directly into the optimization framework by modifying the economic parameters used for block valuation. This allowed the influence of economic variability on pit configuration and project valuation to

be evaluated within the optimization process itself.

The study demonstrates that scenario-based economic analysis can provide valuable insight into the robustness of mine planning outcomes. By comparing optimization results under different economic regimes, mine planners can better understand how project valuation may respond to variations in commodity prices and operating costs. Such analysis can support strategic decision-making by highlighting the dependence of project profitability on economic assumptions embedded in deterministic optimization models.

However, the findings of this research should be interpreted within the limitations of the applied methodology. The optimization framework remained deterministic, with commodity prices and operating costs treated as fixed parameters within each scenario. Year-to-year price fluctuations, stochastic price behavior, and dynamic economic conditions over the life of the mine were not modeled. Additionally, operating cost variability was represented using oil price growth as a proxy for energy-related expenditures, while other cost components were not independently evaluated. Geological uncertainty and geotechnical variability were also not incorporated in the analysis, as the study relied on a single deterministic block model and constant slope parameters.

By the way of conclusion, despite these limitations, the results offer a clear demonstration of the effect of the economic conditions on the outcome of the deterministic pit optimization. From the results, it is confirmed that the economic environment used during the optimization process plays a crucial role in the determination of the pit geometry and the valuation of the project. Therefore, the evaluation of different economic environments during the mine planning stage could offer a better understanding of the effect of the economic conditions on the strategic planning of the mining project.

6.2 Recommendations for Future Research

While this study provides insight into how alternative economic regimes influence deterministic open pit optimization outcomes, several opportunities exist for extending the analysis in future research. These opportunities arise from the methodological assumptions adopted in the present study and from the simplified representation of economic and geological factors within the

optimization framework.

Future research could extend the deterministic framework applied in this study by incorporating stochastic optimization approaches that explicitly represent economic uncertainty. In the present analysis, commodity prices and operating costs were treated as fixed parameters within each scenario. Although this structure allowed clear comparison between economic regimes, it does not capture the probabilistic nature of commodity markets. The integration of stochastic modeling techniques could allow future studies to evaluate how price volatility and uncertainty influence pit limits, production schedules, and project valuation.

Besides, application of dynamic commodity price modeling within the optimization process could be also conducted as a part of future work. In this study, economic scenarios were constructed using average growth rates applied as static adjustments to baseline prices. This approach represents differences between long-term economic regimes but does not capture year-to-year price variability over the life of the mine. Future work could incorporate time-dependent commodity prices within the optimization workflow in order to evaluate how changing market conditions affect optimal extraction strategies and discounted project value.

Another area for future investigation relates to the representation of operating costs within the economic model. In the present study, operating cost adjustments were linked to oil price growth rates in order to account for energy-related cost variation. Although this approach reflects an important component of mining operating costs, it represents a simplified approximation of cost variability. Future research could incorporate more detailed cost models that explicitly account for additional cost drivers such as labour, equipment utilization, maintenance cycles, and consumables to improve the realism of economic evaluations. Future studies could also examine the influence of geological uncertainty on optimization outcomes. The analysis presented in this study relied on a single deterministic block model that was treated as fixed and fully known. In practice, mineral deposits are subject to uncertainty in grade distribution and geological continuity.

Incorporating multiple geological realizations or resource classification variability into the optimization process would allow future research to evaluate how geological uncertainty interacts

with economic assumptions in determining optimal pit limits and project valuation. Finally, further research may investigate the combined influence of economic variability and geotechnical conditions on pit optimization. In this study, slope angles and geotechnical parameters were assumed to remain constant across all evaluated scenarios in order to isolate the effect of economic parameter variation. Future studies could explore alternative slope configurations or geotechnical uncertainty to assess how interactions between economic and geotechnical factors influence optimal pit geometry and project value.

In summary, an extension to the deterministic optimization model presented in this study, considering economic uncertainty, dynamic pricing, a more sophisticated cost model, and geological variability, will give a broader understanding of the combined effect of these sources of uncertainty on mine planning decisions. This will allow for the development of a more robust optimization model to accommodate changes in economic and geological conditions for open pit mines.

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Appendixes

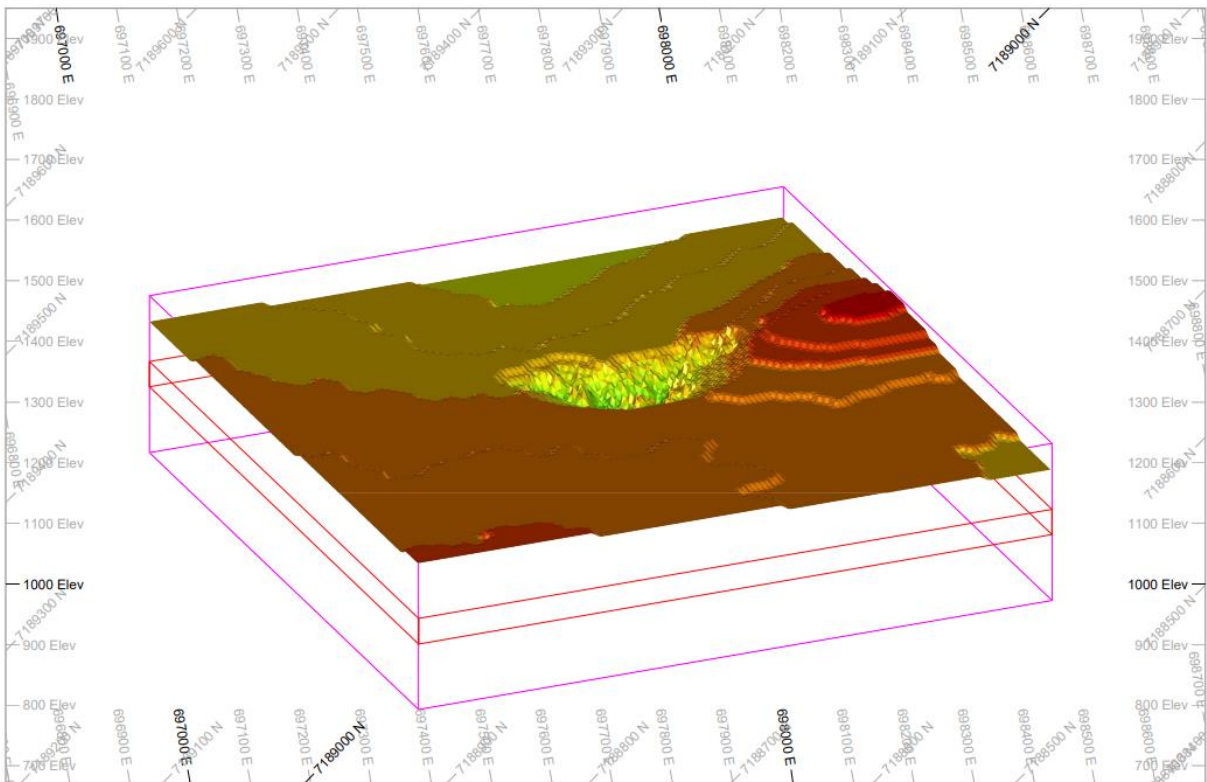


Figure 11. Pushback 1 for Scenario 1.

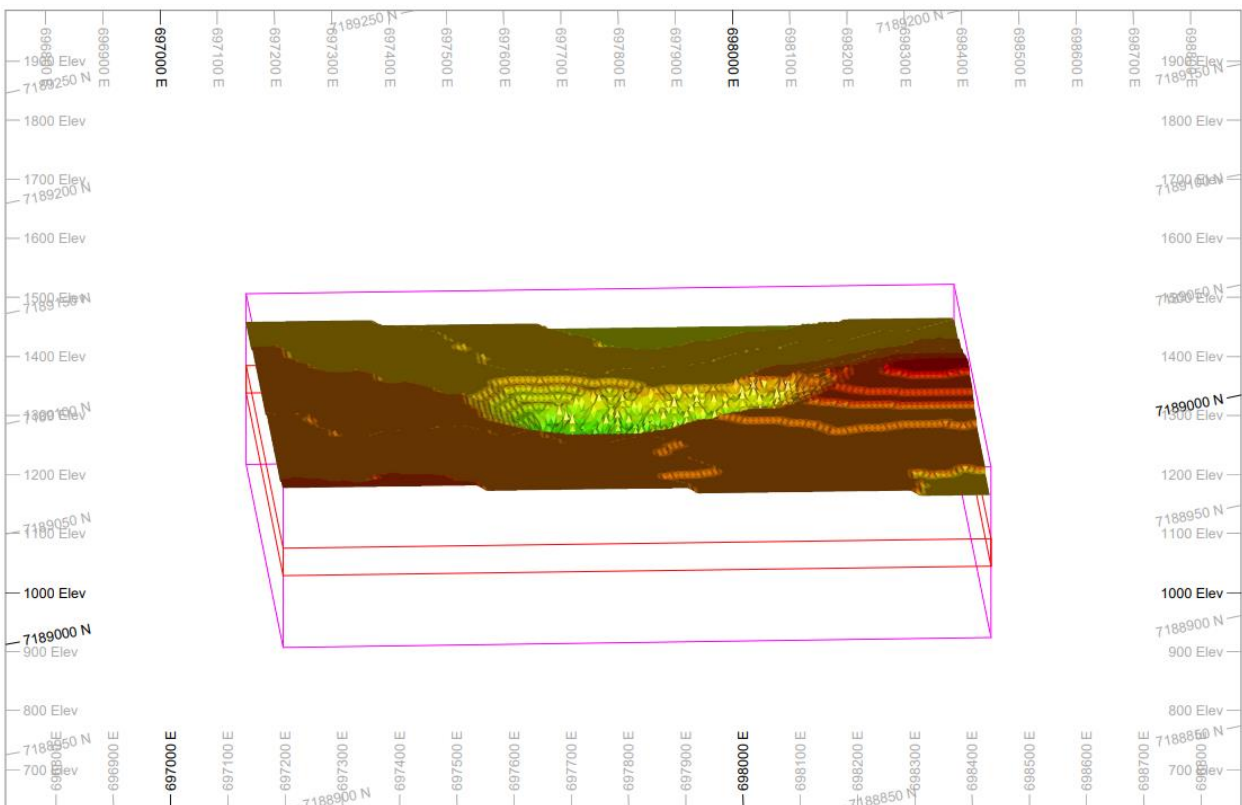


Figure 12. Pushback 2 for Scenario 1

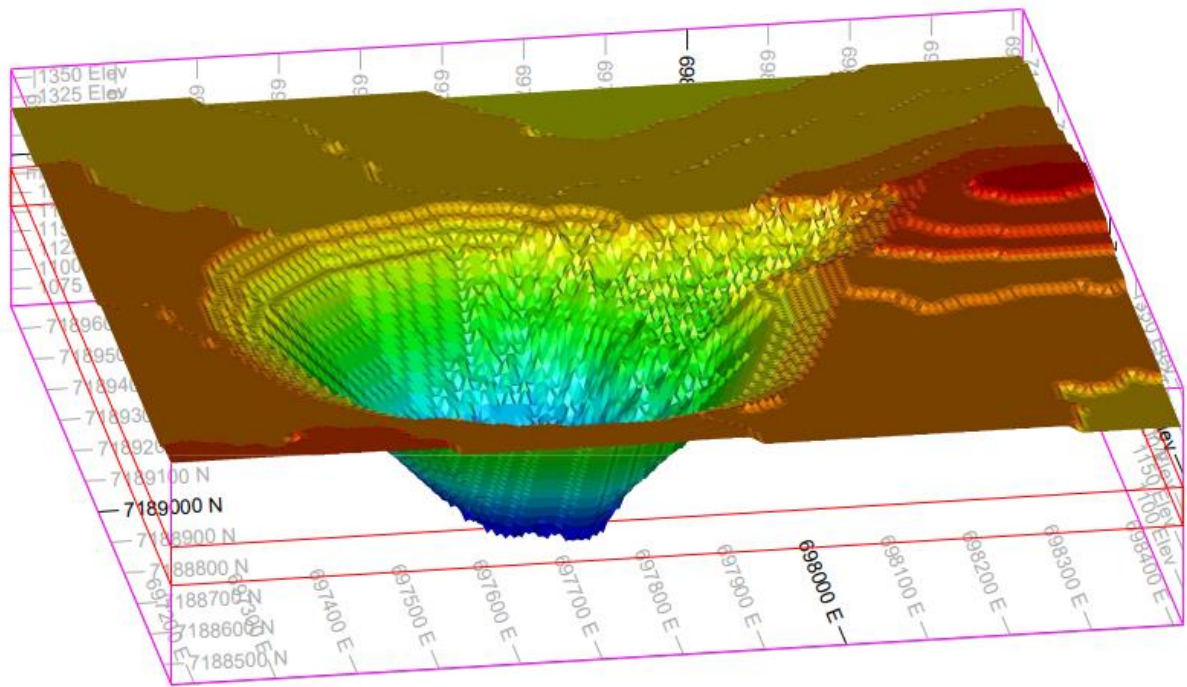


Figure 13. Pushback 3 for Scenario 1

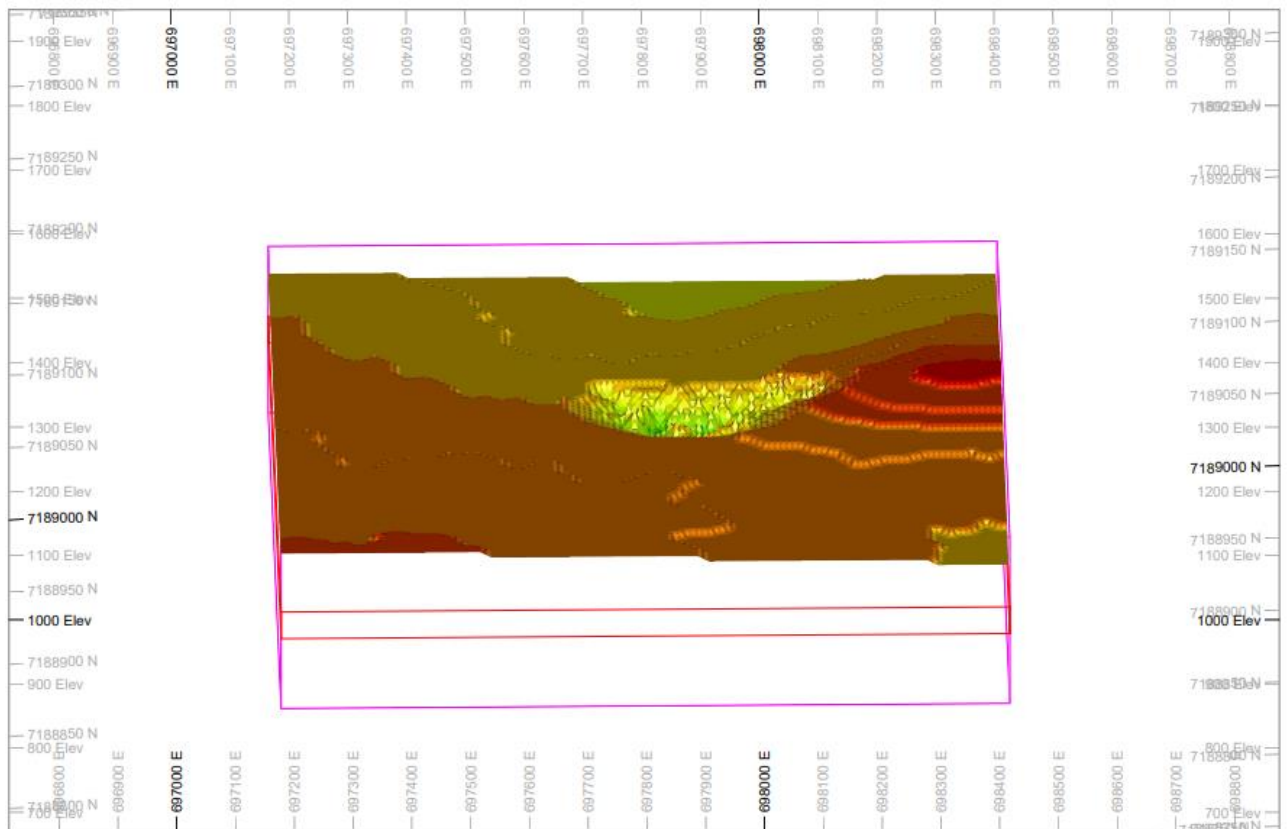


Figure 14. Pushback 1 for Scenario 2

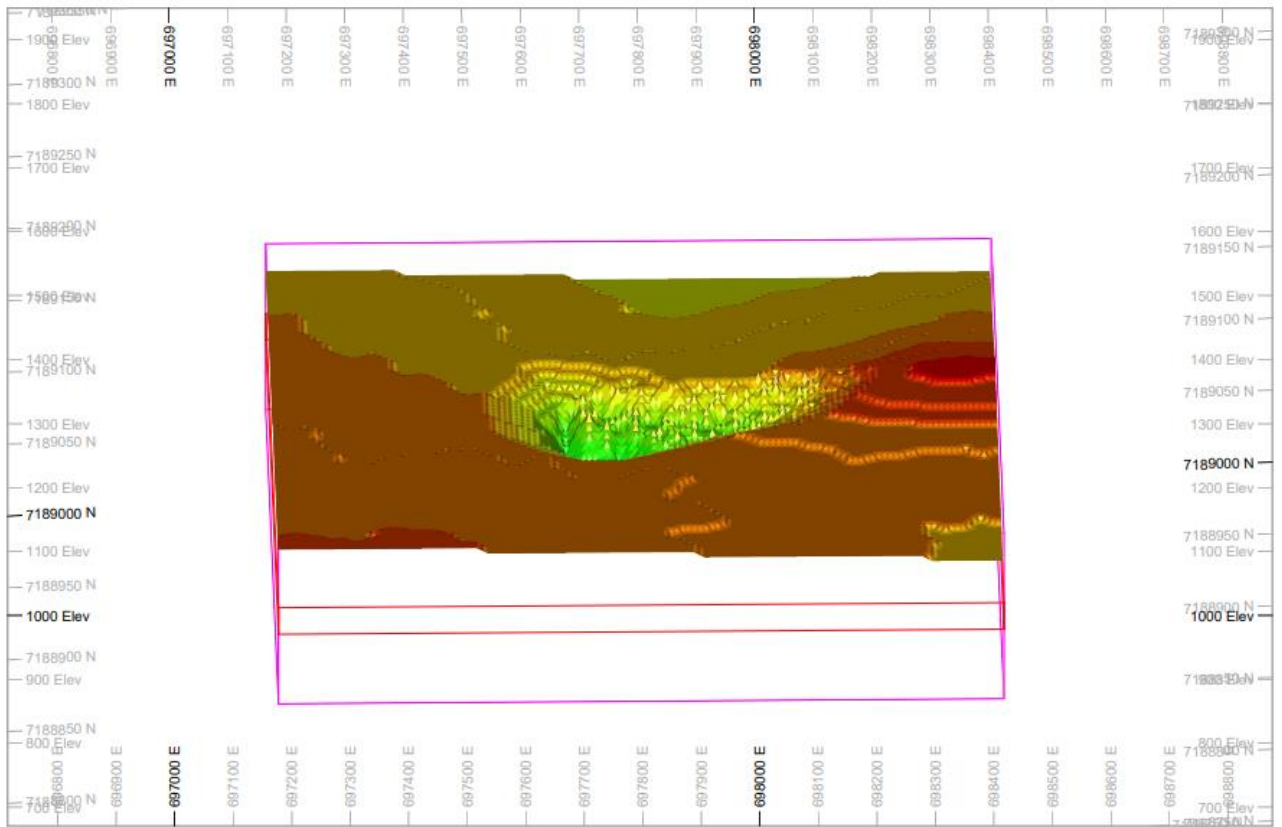


Figure 15. Pushback 2 for Scenario 2

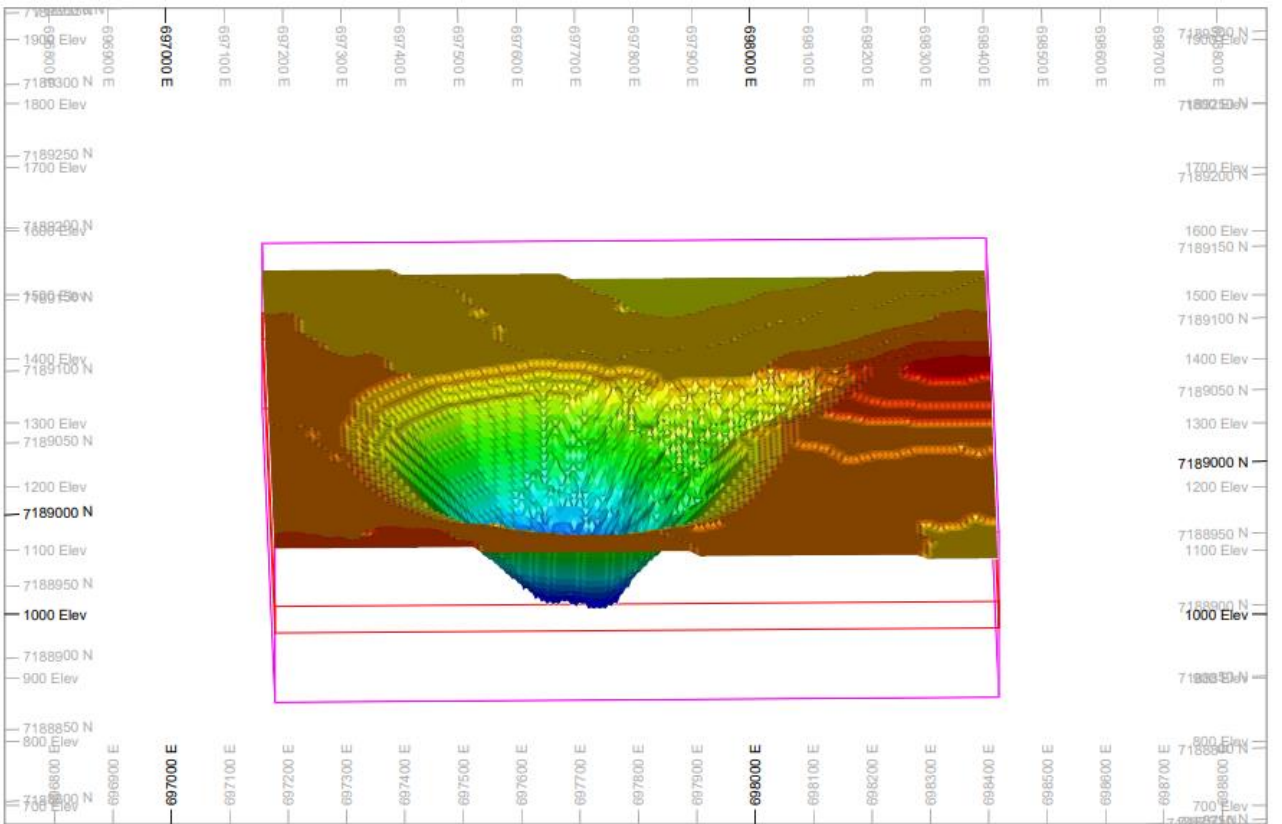


Figure 16. Pushback 3 for Scenario 2

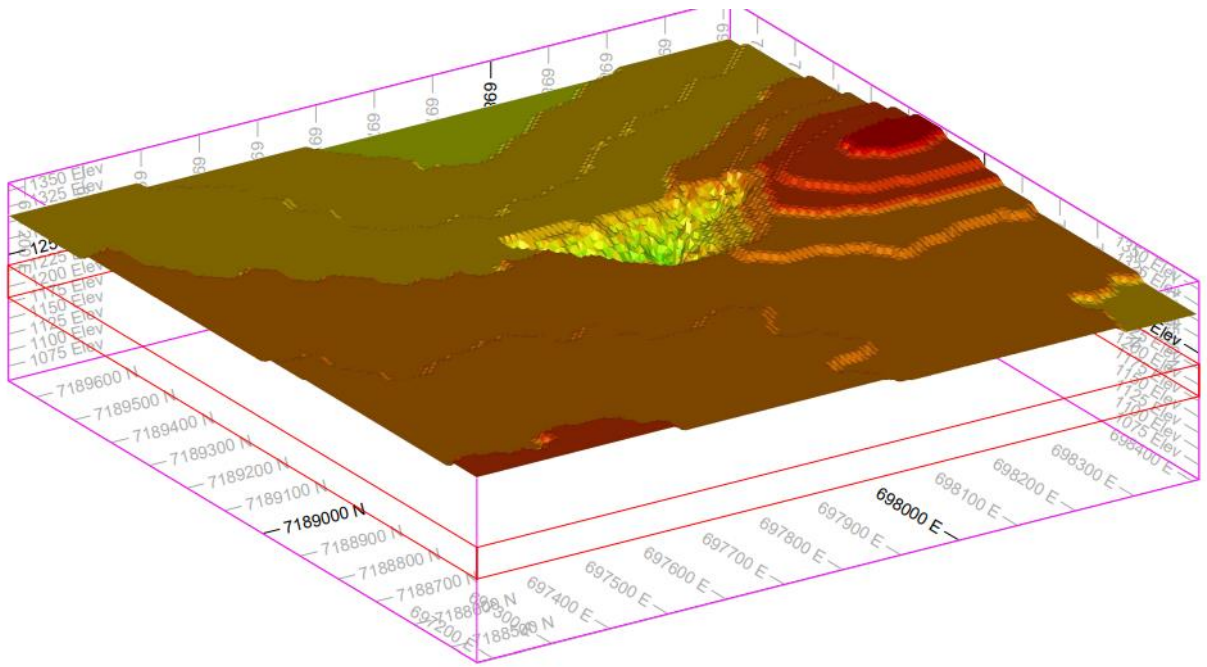


Figure 17. Pushback 1 for Scenario 3

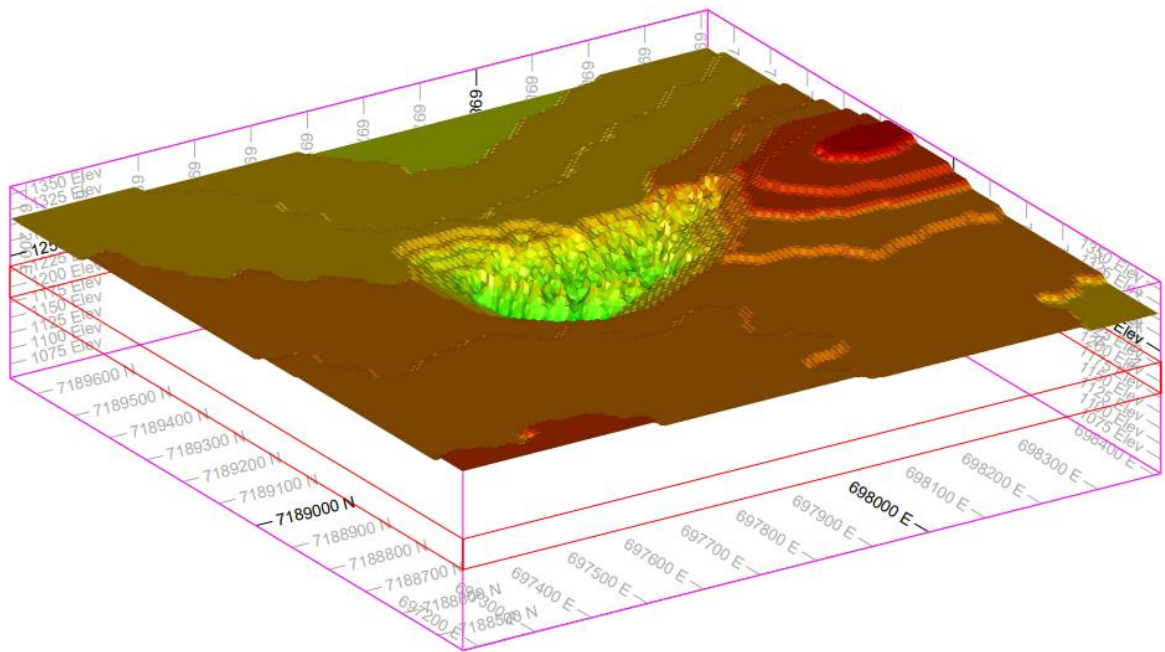


Figure 18. Pushback 2 for Scenario 3

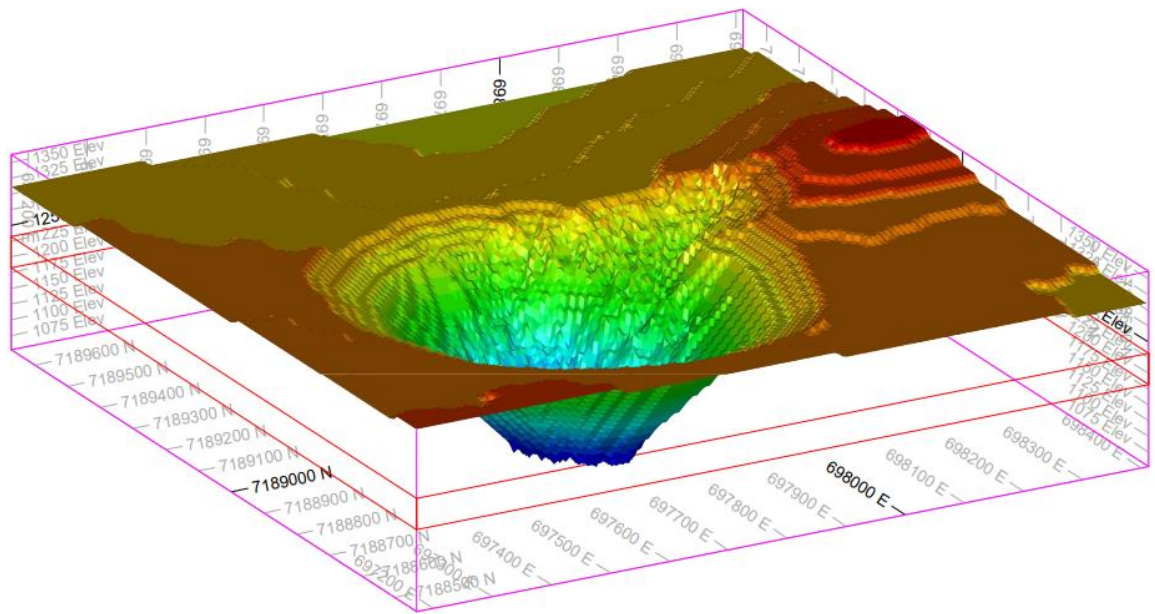


Figure 19. Pushback 3 for Scenario 3