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Reducing Waste Handling by Optimizing Slope Angles in Compact Rocks: A Contribution to the Circular Economy

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Abstract

To extract ore from open pit mines, the associated waste material must also be removed. In most mining operations, the amount of waste rock is greater than the amount of ore. Waste from the pits is usually disposed of in piles, which results in environmental impacts, such as alterations in the natural landscape, possible contamination of soil and water, and the generation of dust and particulates. One way to reduce these environmental impacts and achieve a circular economy (CE) is to use waste rock to construct the pavement layers of mine roads. Another possibility would be to move only the amount of waste necessary to release the ore of interest; in addition to reducing costs, this approach would reduce the volume of waste disposed of in piles. In this study, to reduce the movement of this compact waste, a change in the planned slope is proposed, and the compact waste and surplus material in a long-term mining plan are evaluated. The new optimized geometries, which meet the requirements for road pavement material and remain stable, as indicated by 2D geotechnical finite element modeling, were incorporated into the mining plan of Pit A, an iron mining complex in northern Brazil. The new mining plan was further subjected to economic analysis, which revealed the variations in the tonnage of ore and waste rock (mostly fresh mafic), as well as the change in the net present value (NPV), compared with the original mining plan. The results indicated that the change in geometry led to a reduction of 4.42 Mt in fresh mafic movement. This reduction directly impacted the NPV of the mine plan, with an increase of US$6.88 million.

Keywords

Mine Planning, Circular Economy, Fresh Mafic, Net Present Value

1. Introduction

According to Robertson (1987), waste rock is a type of waste composed of natural aggregates formed by one or more minerals without economic value. This material is removed from mines to allow access to the ore of interest, and although waste rock is extracted during operation, it is not sent to processing. Instead, it is usually disposed of in waste piles.

Aragão (2008) reported that the movement of waste material can negatively impact mine development, with economic, safety and environmental consequences. This is due to the large volume of waste material handled during operation, the limited availability of suitable areas for waste disposal and the requirements imposed by regulatory agencies.

The MMA (2009) and Gomes (2017) suggested that to minimize the amount of waste sent to piles, five basic principles of environmental education should be adopted: reduce, reuse, repurpose, recycle and rethink. In addition, Gontijo (2021) noted that mining companies can adopt strategic alternatives, such as partnerships with cooperatives, public agencies and consumers, to realize the use of waste material. Some potential uses include dam rockfill, embankment filler, pavement material, civil construction aggregates, etc.

Given the constant generation of waste rock in large volumes during mining operations, as well as the environmental impacts associated with the disposal of waste rock in piles, any alternatives that can reduce the amount generated or reuse this material are of great interest to the sector. Thus, reusing waste rock has emerged as an essential strategy to minimize environmental impacts, promote sustainability in the mining industry and stimulate technological innovation (Carneiro & Mendes, 2024).

According to authors such as Castro-Gomes et al. (2011), Akbulut and Gürer (2007), Yellishetty et al. (2008), and Hebhoub et al. (2011), waste material can be used in asphalt pavement and in the production of concrete. Benarchid et al. (2018) emphasized that although waste material can replace common natural coarse aggregates, civil engineering regulations and environmental requirements must be met. However, the reuse of waste on a large scale is still limited by transportation and other economic factors. Therefore, it is necessary to seek value-adding solutions to promote the reuse of waste material.

Waste use methods in which the high value of the product is not mitigated by transportation costs have strategic potential. Mun et al. (2007) reported that waste fines from abandoned mines can be used in polyester mortars. Raupp-Pereira et al. (2008) reported that waste calcium carbonate can be used in the production of Portland cement.

According to Kirchherr et al. (2017), the circular economy (CE) is based on the principle of minimizing waste and reintegrating materials into the economic system. Thus, this approach can simultaneously promote economic growth and reduce environmental impacts. The main objective of the CE is to achieve financial prosperity while preserving environmental health. Therefore, it is necessary to adopt strategies such as reusing waste (waste rock or tailings) from one process in another process or reintegrating this waste into the original process to reduce environmental damage.

The ICMM (2017) reported that mining operations have great potential for adopting a circular approach. In addition to considering the environmental and social impacts of their activities, companies in this sector can implement actions to minimize negative effects, share good practices and reduce waste. Mining generates a significant amount of waste, and many of these materials can be reused, either within the production chain itself or in other applications. For example, waste rock can be used as backfill, in landscaping or as aggregates in road construction. Such applications represent how adopting the CE in mining can transform waste into resources and promote a more sustainable industry.

The CE preserves the value of materials by keeping them available, as opposed to discarding them. In terms of mining waste, the CE provides a means of creating value from these materials, keeping the resources in use and limiting their wastage (Antikainen & Valkokari, 2016; Lébre et al., 2017; Ritzén & Sandström, 2017).

Young et al. (2021) reported that establishing circular practices creates mechanisms to reduce water and energy consumption, decrease CO_2 emissions and eliminate waste generation. Such practices help reduce operating costs, especially those associated with risk management and resource consumption. Waste rock that is stored and exposed to climatic conditions can generate significant environmental impacts over time, which often manifest years after mine closure. By minimizing the accumulation of waste rock, circular practices reduce these environmental risks and the related costs. The implementation of circular strategies reinforces a company’s commitment to sustainable and responsible production, strengthening its reputation. In addition, it favors access to markets that prioritize sustainability, attracts responsible investments and improves capacity.

Jose et al. (2024) stated that applying CE principles in waste management can make the mining sector more efficient and sustainable. By replacing the simple disposal of waste with the reuse of resources, the industry can transform environmental liabilities into economic assets, promoting more responsible practices aligned with sustainability.

El Machi and Hakkou (2024) emphasized that overburden accumulation from mine operations can cause dangerous environmental problems, such as landslides, agricultural land degradation and acid drainage. Therefore, the authors suggested that partnerships be formed between the mining and construction industries, with the objective of reusing waste in various construction projects. The adoption of a CE connecting these two sectors is a key strategy for solving the above environmental problems while creating opportunities for corporate and national socioeconomic development.

The present study proposes an alternative based on optimizing the overall slope angle while optimizing the bench face angle so that the movement of waste material is reduced. The approach will be applied in an iron mine in a mining complex in northern Brazil. The change in slope angles allows better management of the waste material that is moved, reducing the associated costs and increasing the NPV of the project.

2. Materials and Methods

With the objective of reducing the movement of compact waste material, the proposed methodology was designed to optimize the overall slope angle and, consequently, the bench face angle. Thus, it is expected that in addition to reducing waste movement, the associated costs will also be reduced, and the NPV of the project will increase.

The proposed method is based on the use of trigonometric calculations to define new angles applicable to pit design and is supported by geotechnical modeling. A general scheme of the methodological approach is given in the flowchart in **Figure 1**. The steps of the methodology are described in the following sections.

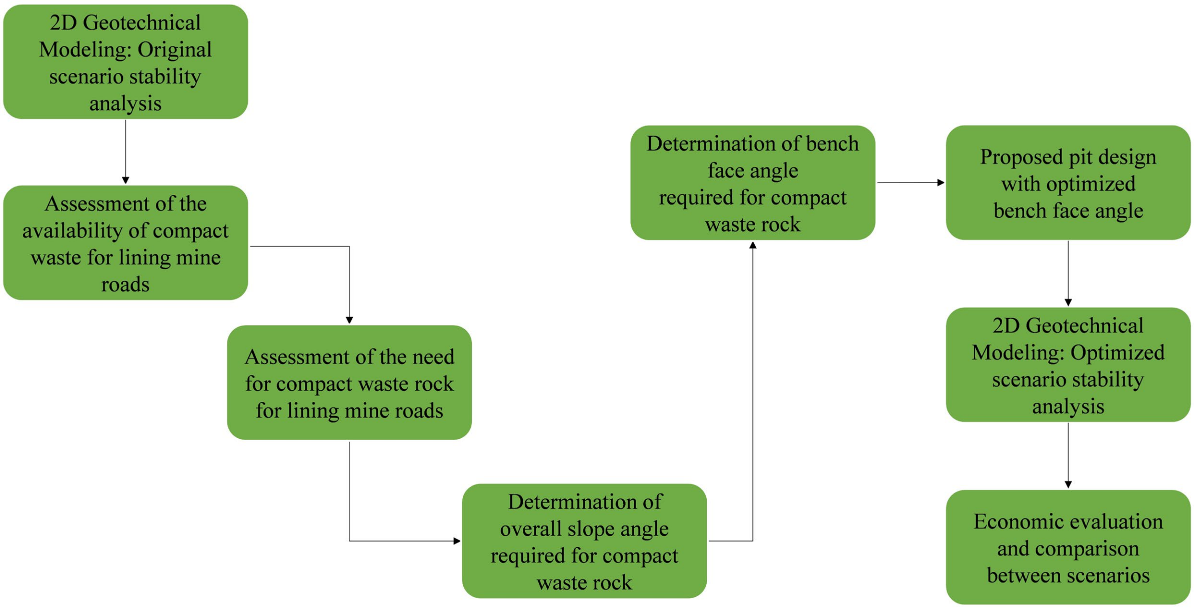

Figure 1. Flowchart of the proposed methodology.

2.1. Geotechnical Parameters

In the last 5 years, several geotechnical studies focusing on the mining complex in this case study were performed. Years of data were combined to define the geotechnical parameters of the lithologies of the deposit. According to the type of lithology, the parameters correspond to different failure criteria, such as the generalized Hoek-Brown (Hoek et al., 2002) and Mohr-Coulomb (Coulomb, 1776; Mohr, 1900) criteria. **Table 1** shows the data that were used to calibrate the geotechnical instruments used for stability analysis. These parameter values were maintained throughout the study due to compatibility with the block model and the lithological model.

Table 1. Parameters used in geotechnical modeling.

Rock Type	ID	γ_d (kN/m³)	γ_s (kN/m³)	c' (kPa)	φ (degree)	GSI	m_i	σ_c (MPa)	E (MPa)	ν
Fresh mafic	MS	29	30	3200	50	70	7	151	29.66	0.22
Semi-decomposed mafic	MSD	30	32	240	32	45	3	13.98	27.56	0.22
Decomposed mafic	MD	18.5	20	86	28	50	2	0.825	0.91	0.30
Compact hematite	HC	37	37	250	45			27.56	27.56	0.22
Friable hematite	HF	37	39	124	38				0.38	0.28
Jaspilite	JP	37	38	3750	48	60	7	167	45.87	0.21
Chemical canga	CQ	30	30	65	43				2.00	0.35
Structural canga	CE	30	30	65	43				2.00	0.35
Manganiferous hematite	HMN	37	39	75	30					

γ_d: dry specific weight; γ_s: saturated specific weight; c': cohesion; φ: friction angle; GSI: geological strength index; m_i: material constant for the intact rock; σ_c: unconfined compressive strength; E: elastic modulus; ν: viscosity coefficient.

2.2. Stability Analysis of the Original Scenario

Stability analysis was performed using the finite element method (FEM) in two dimensions (2D), prioritizing the pit areas with compact rocks, especially in the fresh mafic region. The FEM is the best approach for elastic considerations of slope changes.

FEM modeling is based on geological, piezometric and structural models and is used to evaluate long-term mine plans, where suitable rocks are more common. Finite element models need to obey geometric rules that often do not apply in real geological scenarios; therefore, the geometry of the lithologies must be modified to sensitively adapt the geological models to the FEM.

To represent the behavior of compact rocks such as fresh mafic and jaspilite, the generalized Hoek-Brown failure criterion was used. For the remaining friable materials, the Mohr-Coulomb criterion was used. Figure 2 shows the fresh mafic region in the eastern portion of Pit A, with the cross-sections indicated.

Six cross-sections were defined for the 2D finite element stability analysis. To evaluate the degree of stability of the overall slope, acceptability criteria based on several studies were used, such as those by Swan & Sepulveda (2001), Hoek (2007), and Read & Stacey (2009), which consider the factor of safety (FoS) as a reference. Table 2 summarizes the criteria considered.

Table 2. Acceptability criteria for stability analyses.

Criterion	FoS: Overall slope angle
Unstable	FoS ≤ 1.1
Stable, does not meet the acceptability criterion	1.1 < FoS ≤ 1.3
Stable, meets the acceptability criterion	1.3 < FoS ≤ 1.4
Stable, conservative	FoS > 1.4

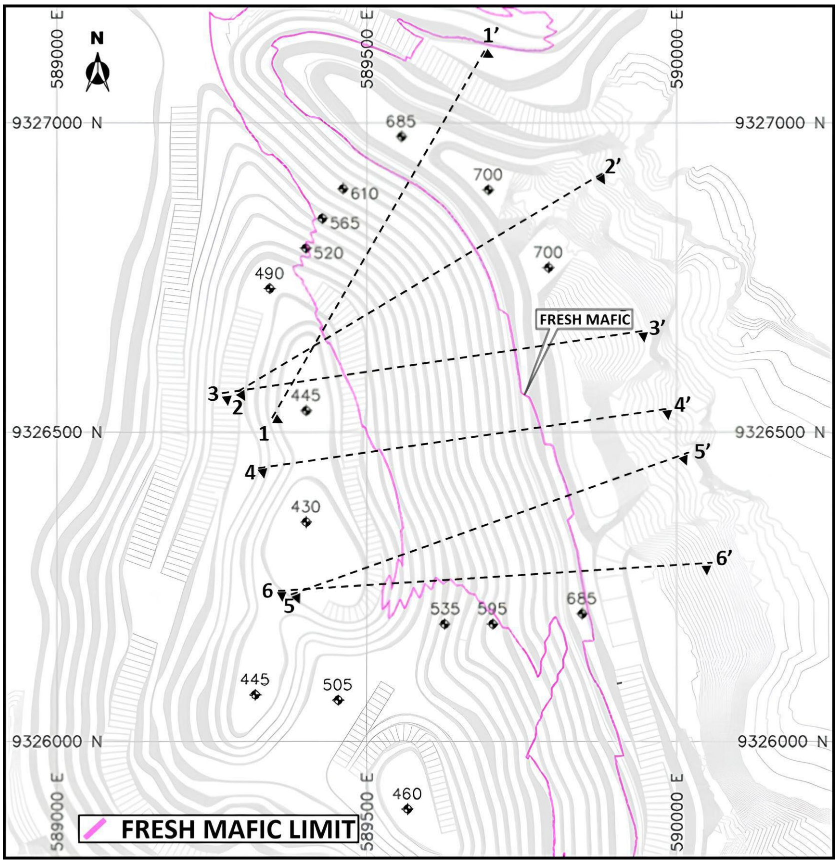

Figure 2. Fresh mafic region in Pit A.

2.3. Availability of Compact Waste

The Pit A mining complex is characterized by a significant amount of material movement, which is associated with very long access routes for off-road trucks. With more than 100 kilometers of access routes in the complex, there is high demand for suitable material for maintaining the pavement of mine roads, access routes to tailings deposits and other access routes to the complex (Campos & Peroni, 2023).

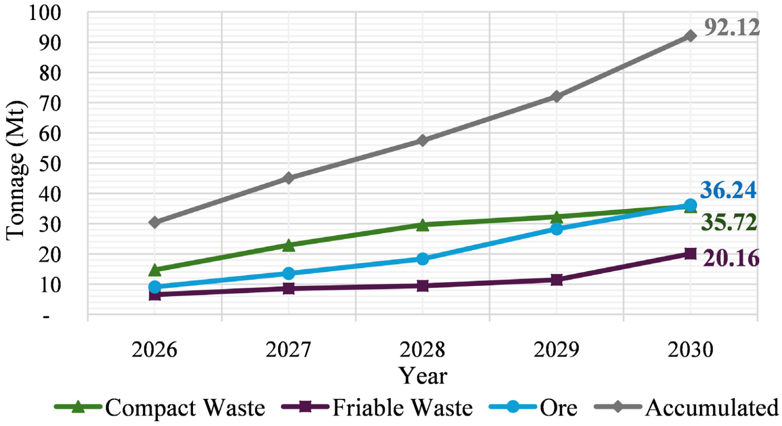

Figure 3. Final pit tonnages.

Pit A is predicted to be fully exhausted by 2030, and the tonnage of compact waste, represented by fresh mafic rocks and jaspilite, can be estimated on the basis of the mining plan. Thus, **Figure 3** shows a graph of the planned tonnages of ore, friable waste and compact waste accumulated annually during the remainder of the mining period.

The graph shows that the amount of compact waste in Pit A in the last 5 years of operation will be 36.24 Mt. This value was used to determine the need for compact waste to construct pavement for roads in Pit A, as will be demonstrated in the next section.

2.4. Requirement for Compact Waste for Road Pavement

A common approach for designing the total thickness of pavement layers on mining roads is based on the California bearing ratio (CBR). This method evaluates the bearing capacity of the pavement layers to avoid plastic failure in the subbase under static loading.

According to Kaufmann and Ault (1977), CBR is calculated as the percentage ratio between the pressure applied by a piston to compact a soil sample under analysis and the pressure exerted under the same conditions on a standard reference soil sample. This reference sample is usually composed of high-quality, well-graded crushed stone with a CBR equal to 100%.

The CBR for a given material (pavement layer or subbase) must be precisely determined in the laboratory. In this process, different wet conditions are considered to represent seasonal variations and obtain the corresponding CBR values.

According to Thompson et al. (2019), it is essential to use a strong structural layer to protect the weaker layers of the subbase. A common material for this structural layer is blasted rock, which is often available in mining operations, because it provides the strength necessary to withstand the high loads applied by large off-highway trucks.

Design methods based on empirical data have a theoretical foundation supported by the literature, but they are also supported by results obtained from deterministic calculations and by analysis of performance under the different operational and climatic conditions of each mine. Historically, mining complexes have well-defined rainy and dry seasons. The variation in the volume of precipitation between these periods directly impacts operations and influences the performance of equipment, increasing the need for the maintenance of roads.

The CBR, the dynamics of equipment allocation, daily observations and seasonality can be used to determine the amount of material required for pavement construction to meet short- and medium-term operational demands. For the long term, an estimate based on previous experience is made. **Figure 4** shows a graph comparing the amount of compact waste material required for pavement with the amount of compact waste material available in Pit A.

2.5. Determination of the Overall Slope Angle

The original geometry planned for the final slope of Pit A intersects outcrops of fresh mafic rock. Because these outcrops are composed of waste rock, a new geometry is proposed here in which the new slope reduces the movement of waste material without affecting the amount of compact material required for the maintenance of mine roads.

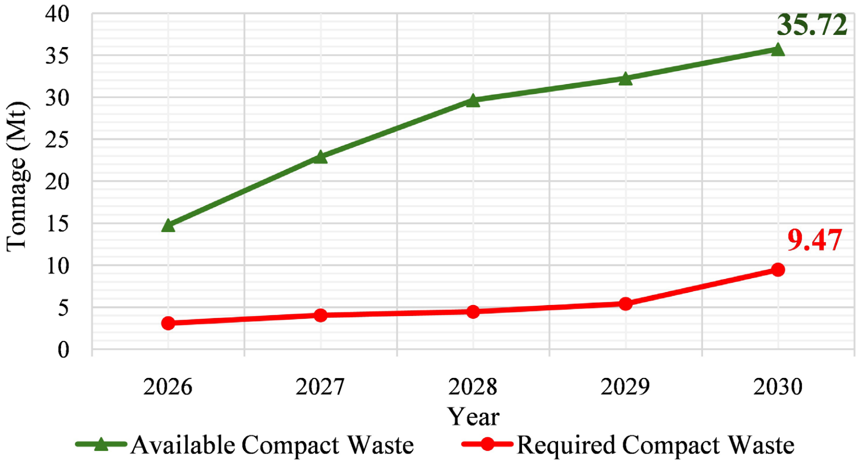

Figure 4. Required vs. available compact waste.

To address this challenge, a simplification was adopted in which the volume of surplus fresh mafic is located between the original face and the new face of the proposed slope. This volume is estimated through parallel sections along the fresh mafic outcrop. The geometry of this section corresponds to the scalene triangle ABC formed between the original face and the new face, as shown in **Figure 5**.

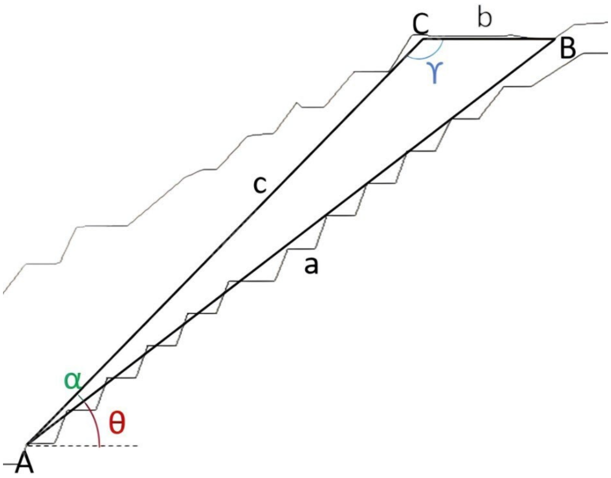

Figure 5. Sketch of the geometric problem.

Considering that the internal mass of material in the triangle propagates in a line, since the density of the material and the area of the scalene triangle are known, the excess mass of fresh mafic can be calculated to determine the angle α needed to increase the slope angle θ. Equation (1) shows the calculation of α, which is derived from the sine law, the equation of the area of the scalene triangle and the trigonometric identity.

$$\alpha = \tan^{-1}\left\{\frac{1}{\frac{a^2 \times L \times \rho}{2 \times m} + \frac{1}{\tan\left(180^\circ - \theta\right)}}\right\} \tag{1}$$

where:

α: angle added to the overall slope angle (degree);

θ: overall slope angle (degree);

a: length of the side adjacent to θ and α (m);

L: length of the propagation line of the parallel section (m);

ρ: density of the material in situ (t/m^3);

m: mass of compact fresh mafic material in excess of the required amount of compact material (t).

2.6. Determination of the Bench Face Angle

To achieve the calculated overall angle for fresh mafic, additional horizontal space is needed. However, bench heights, operational berm widths and geotechnical berm widths are fixed in the mining plane and should not be modified. Therefore, the geometric aspect that can be changed to provide horizontal space in the fresh mafic range is the operational slope face, which is currently set to a 70˚ inclination.

Considering that the overall slope is a right triangle, the length of the base of this triangle can be trigonometrically determined from the overall angle and the slope height. This measure includes a certain number of benches, operational berms and geotechnical berms. Likewise, the face slope can also be considered a right triangle. Thus, from the length of the base of the triangle of the overall slope and the number of benches, operational berms and geotechnical berms, the length of the base of the triangle of the face slope can be determined. The new bench face angle is determined by trigonometry since the height of the bench is known and the length of the base of the triangle has been calculated (Equation (2)).

$$\varphi = \tan^{-1}\left(\frac{h}{\frac{\frac{H}{\tan\theta'} - \left(n_{bo} \times b_o\right) - \left(n_{bg} \times b_g\right)}{N}}\right) \tag{2}$$

where:

φ: new bench face angle (degree);

h: bench height (m);

H: overall slope height (m);

N: number of benches;

θ': overall slope angle (degree);

n_{bo}: number of operational berms;

n_{bg}: number of geotechnical berms in the section;

b_o: width of the operational berm (m);

b_g: width of the geotechnical berm (m).

3. Results and Discussion

3.1. Stability Analysis of the Original Scenario

In this section, the results of the 2D FEM stability analysis are presented. To define the initial in situ stress conditions, the current topography of Pit A, the material characteristics and lithological distribution obtained from the geological model and the water table position obtained from the hydrogeological model were used. **Figures 6-11** show the stability analysis results for each of the 6 cross-sections.

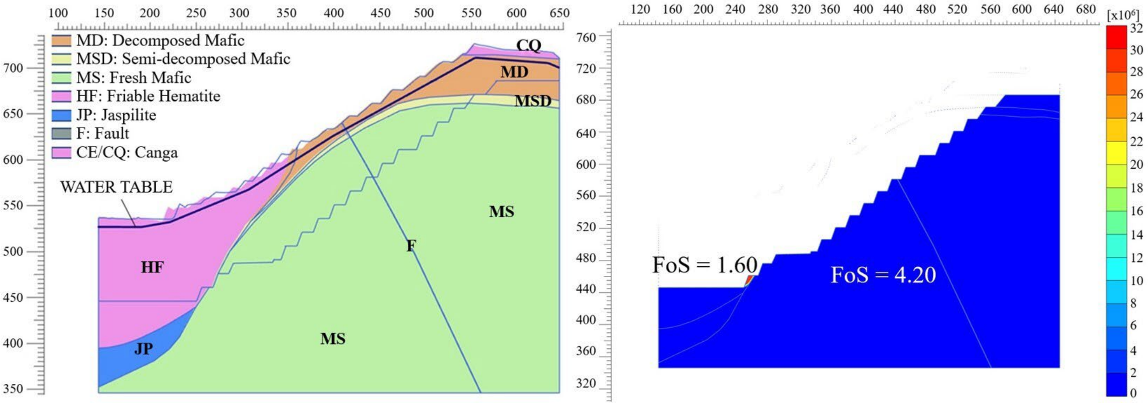

Figure 6. Stability analysis of original Pit A—Section 1-1'.

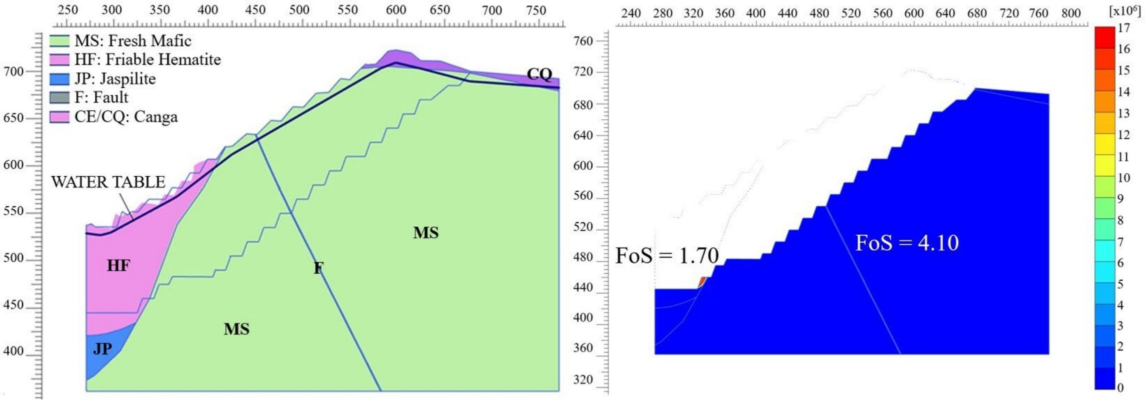

Figure 7. Stability analysis of original Pit A—Section 2-2'.

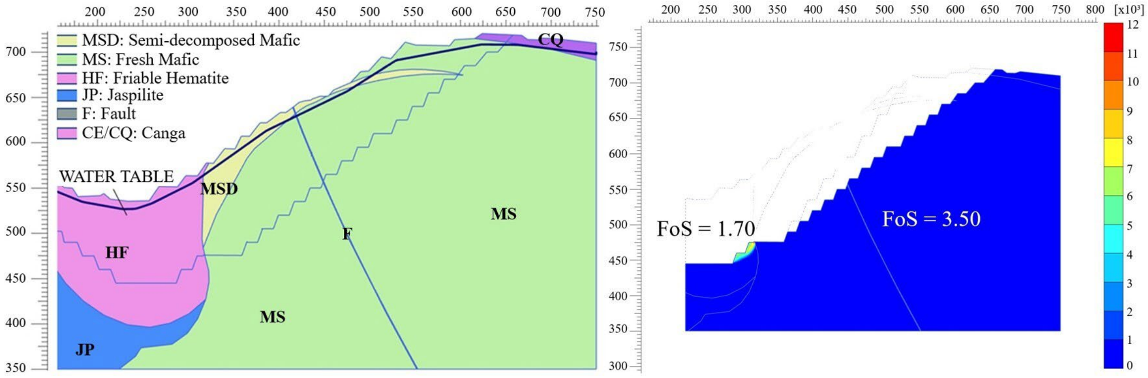

Figure 8. Stability analysis of original Pit A—Section 3-3'.

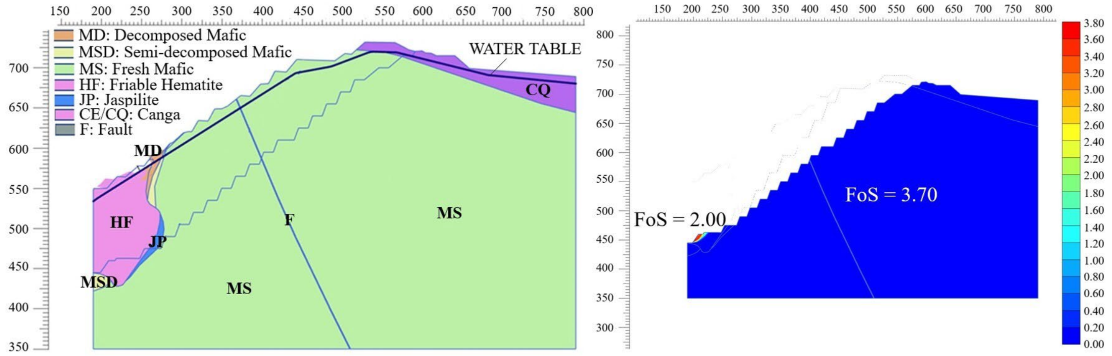

Figure 9. Stability analysis of original Pit A—Section 4-4'.

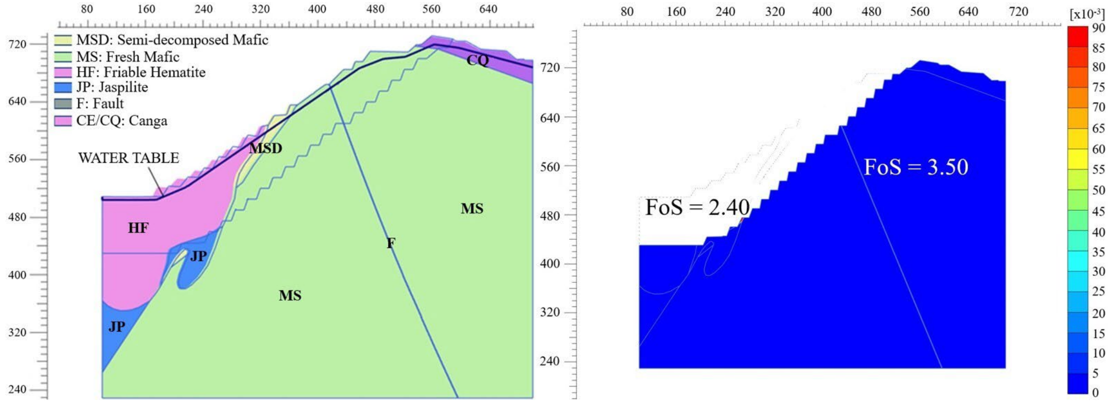

Figure 10. Stability analysis of original Pit A—Section 5-5'.

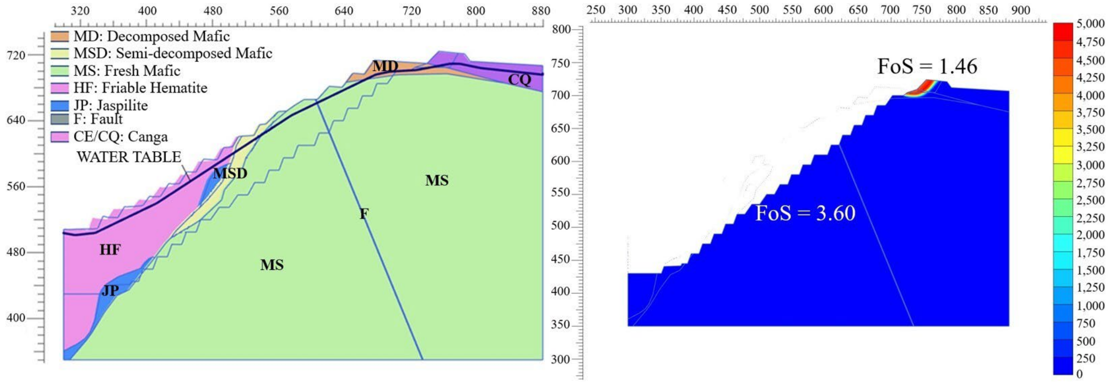

Figure 11. Stability analysis of original Pit A—Section 6-6'.

The stability analysis indicated that the fresh mafic has good strength and will not fail. Thus, the stability of the slopes is not a determining factor influencing changes in geometry, but related analyses were performed to guarantee and confirm slope stability.

3.2. Determination of Slope Angles

Considering the control variables for Pit A, Equation (1) can be applied. Table 3 includes the overall slope angle to ensure that the fresh mafic mass meets the compact material requirements of the mine.

Table 3. Boundary conditions and result of additional α.

Parameter	Value
a (m)	382.00
L (m)	862.00
ρ (t/m^3)	3.00
θ (degree)	41.25
Excess of fresh mafic (Mt)	4.76
α (degree)	3.20
θ' = θ + α (degree)	44.45

In Pit A, a change of 3.20˚ in the overall fresh mafic slope angle would not affect the supply of compact material. Thus, the amount of waste material can be considerably reduced.

To determine the new bench face angle of Pit A, Equation (2) was applied. Table 4 presents the inputs and the results for the proposed geometry.

Table 4. New bench face angle calculation results.

Parameter	Value
h (m)	15
H (m)	165
θ' (degree)	44.45
n_{bo}	9
n_{bg}	1
b_o	12
b_g	20
N	11
φ (degree)	76.30

On the basis of the above calculations, a change in the face slope in fresh mafic regions was proposed. In Pit A, the bench face angle will change from 70˚ to 76.30˚. The geometric criteria adopted were as follows: maintain the elevation of all benches, including the 20 m wide geotechnical bench, which is located at an elevation of 610 m; and maintain the integrity of the access route to the bottom of the pit. Figure 12 shows a plan view, where the optimized slopes are indicated. Figure 13 shows a section with a change in slope compared with the original pit conditions.

3.3. Stability Analysis of the Optimized Scenario

Stability analysis was performed using the same methodology as described above, with the same basement and cross-sections. The results of the 2D FEM stability analysis of optimized Pit A in the six sections are shown in **Figures 14-19**.

The results show that the stability does not change significantly with the change in bench face angle. In addition, the lowest FoS values are observed in friable lithologies, whose geometry was not changed. Nevertheless, these FoSs are in an acceptable range.

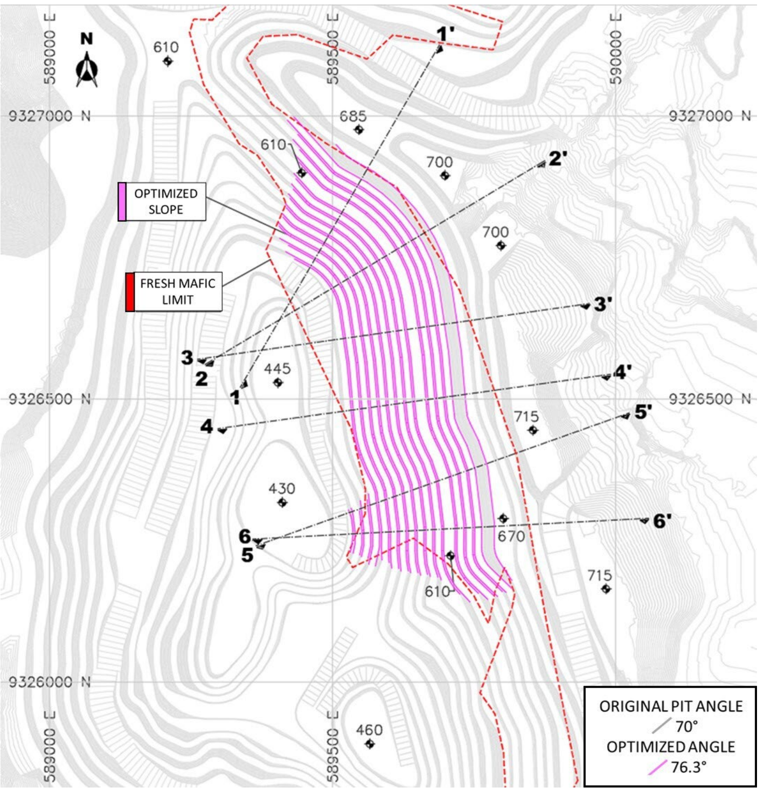

Figure 12. Bench face angle optimization region of Pit A.

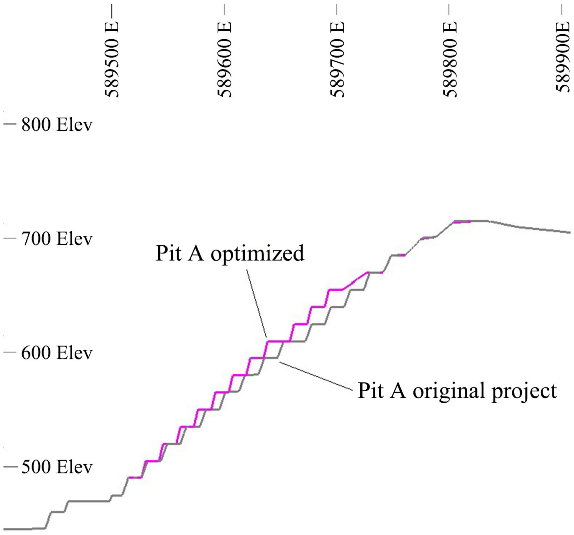

Figure 13. Section 3-3' with the original and optimized layouts of Pit A.

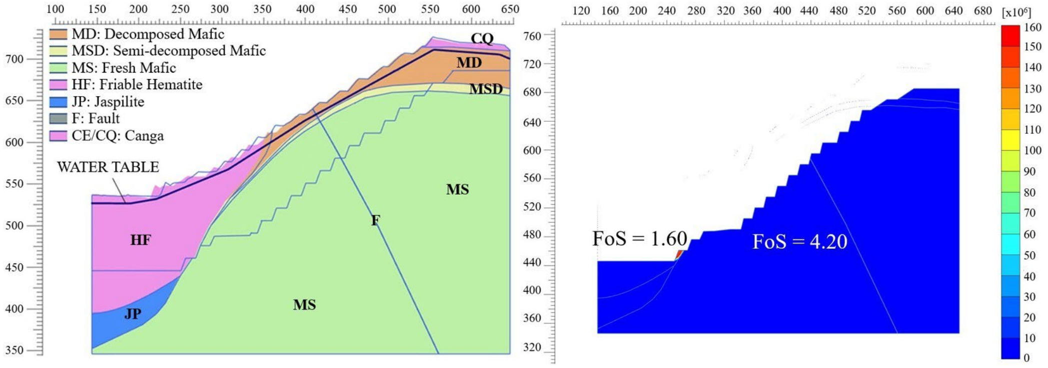

Figure 14. Stability analysis of optimized Pit A—Section 1-1'.

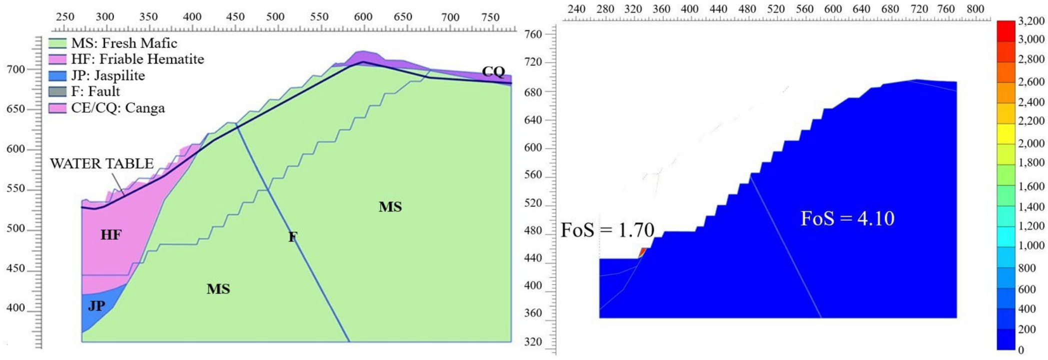

Figure 15. Stability analysis of optimized Pit A—Section 2-2'.

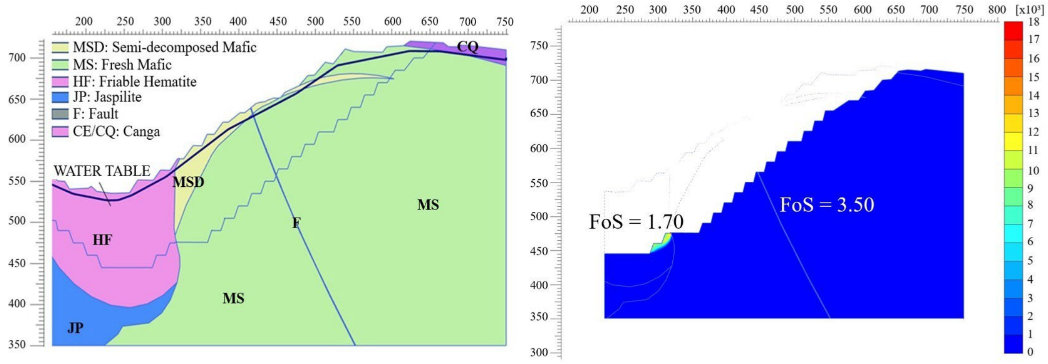

Figure 16. Stability analysis of optimized Pit A—Section 3-3'.

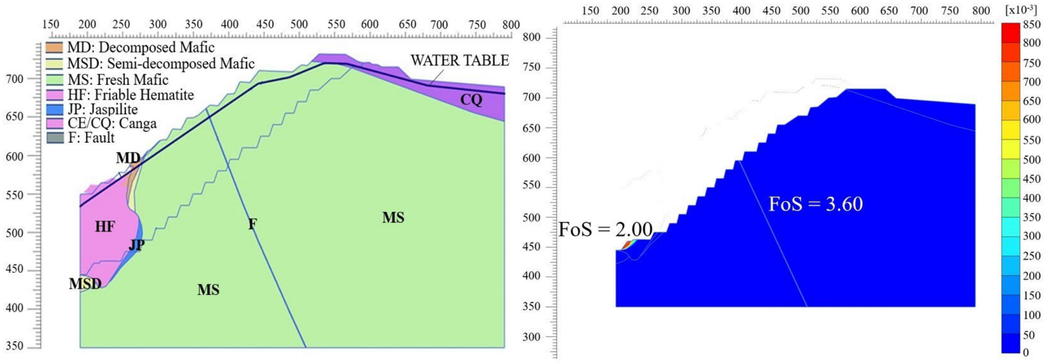

Figure 17. Stability analysis of optimized Pit A—Section 4-4'.

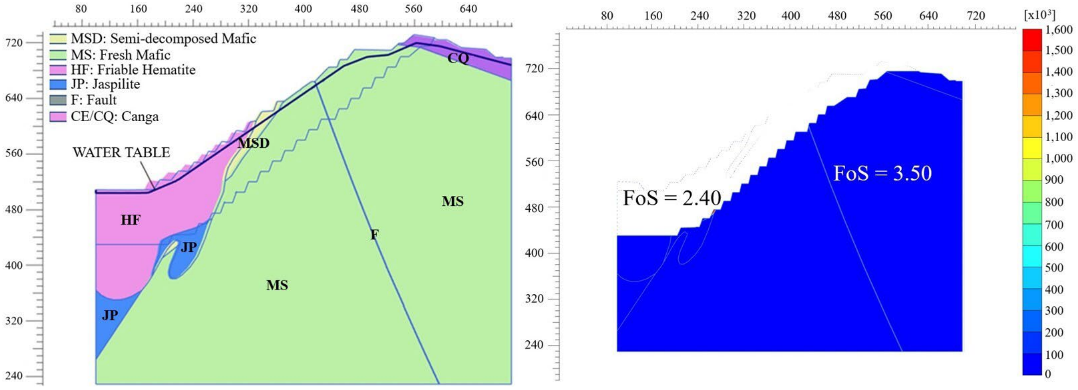

Figure 18. Stability analysis of optimized Pit A—Section 5-5'.

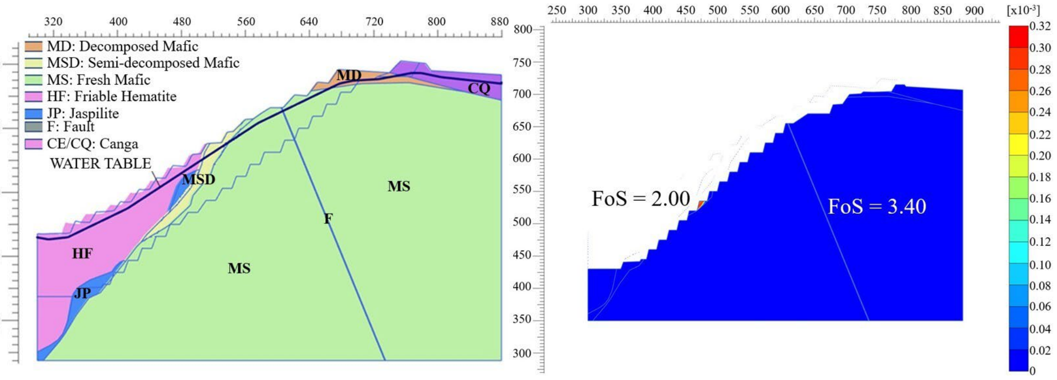

Figure 19. Stability analysis of optimized Pit A—Section 6-6'.

3.4. Economic and Comparative Evaluation between Scenarios

In this section, the original pit scenario is evaluated and compared with the new proposed scenario, considering the change in geometry of the fresh mafic slopes of Pit A. Regarding the potential benefits of applying the proposed methodology, a tonnage assessment of the resources contained in the original and optimized pits was carried out to quantify the masses of ore and waste of the lithologies, as well as to compare their variations. An economic analysis was also performed to compare the variations and verify the impacts on the NPV.

To provide a representative comparison, first, the technical-economic parameters for Pit A provided by the planning team were used. Table 5 summarizes the parameters used.

In addition to these economic parameters, some additional factors, such as the mineral inventory class, where reserves include only the measured and indicated classes, were considered. Regarding the lithologies, all ore of the measured and indicated mineral inventory classes is considered a product, which would result in 100% recovery in the crushing process (in the plant).

The results of the evaluation of the scenarios of the original and optimized Pit A, organized by lithology, are shown in Table 6. The NPV evaluation results are presented in Table 7. Notably, this NPV calculation does not consider capital costs, only operating costs and the other parameters mentioned above. This value represents a more general picture, as if the ore from the entire pit were mined at once, without considering pushbacks and sequencing, which, due to their restrictions, tend to reduce the NPV at each stage.

Table 5. Technical-economic parameters used in pit optimization.

Parameter	Value
Annual production	55,000,000
Mining cost*	1.93 + 0.195 × ATD/1000 US$/t moved
Processing cost	1.8948 US$/t fed
Additional costs**	34.7240 US$/t product
Ore price***	(1.1 × Fegl + 7.289) × (1 − 0.09) US$/t product
Processing recovery	100%
Discount rate	7.5%
ROM moisture	9.0%
Annual production	55,000,000

* Mining cost: This cost depends on the average transport distance (ATD) that the mined block needs to travel to its destination. ** Additional costs include port costs, railway costs, overhead, taxes, selling expenses, product handling expenses, etc. ***Ore price: This value is based on the percentage global iron (FeGl) content.

Table 6. Evaluation of tonnage for the original and optimized Pit A scenarios.

	Original Pit A	Optimized Pit A		
Rock Type	Tonnage (t)	Tonnage (t)	Variation (t)	Variation (%)
CE	55,484	55,484	0	0.00
CQ	3,188,939	3,190,439	1,500	0.05
FMN	171,000	171,000	0	0.00
HC	323,438	323,438	0	0.00
HF	67,009,848	66,948,387	−61,461	−0.09
HMN	242,559	242,559	0	0.00
JP	16,329,473	16,264,639	−64,834	−0.40
MD	35,893,065	35,899,160	6,095	0.02
MS	32,095,999	27,672,690	−4,423,308	−13.78
MSD	7,116,012	6,970,610	−145,401	−2.04
Total	162,425,816	157,738,406	−4,687,410	−2.89

Table 7. Evaluation of NPV for the original and optimized Pit A scenarios.

	Original Pit A	Optimized Pit A	Variation (US$)	Variation (%)
NPV (US$)	1,990,313,907	1,997,190,784	6,876,877	0.35

The proposed change in bench face angle in fresh mafic regions meets the objectives. In Pit A, the fresh mafic mass was reduced by 4.42 Mt. This value was relatively similar to the fresh mafic surplus of 4.76 Mt. Regarding other lithologies, there was an increase in other waste materials, such as chemical canga and decomposed mafic, and a reduction in jaspilite and semi-decomposed mafic. In addition, there was a reduction in ore, represented by friable hematite, of a total of 61.46 kt. These variations resulted in a higher NPV of US$ 6.88 million compared with the original scenario.

4. Conclusion

The incorporation of 2D geotechnical modeling in mine planning offers a promising methodology for optimizing operational stability. Evaluation of the slope stability conditions of Pit A via the 2D FEM revealed that the pit has good stability and that smooth changes in the bench face angle will cause no problems.

The new approach proposed in this study was designed to reduce the excess movement of compact material, specifically fresh mafic rock. A mathematical model was developed to optimize the slope angle on the basis of the difference between the available amount of this rock and the amount required for paving the mine roads.

A change in the overall slope angle in fresh mafic could only be achieved by changing the bench face angle, since the bench heights and berm widths are fixed for operational reasons and to ensure safety of the pit. Therefore, a back calculation was performed to obtain a new bench face angle and to optimize the overall slope angle.

The optimized Pit A reduced fresh mafic waste by approximately 4.42 Mt. Thus, this change resulted in a 0.35% higher NPV when considering the same technical-economic parameters used to generate the original Pit A plan. In absolute values, this percentage is equivalent to US$ 6.88 million.

In general, the proposed slope angle optimization contributes to the CE, as it reduces the amount of material moved. The use of waste rock, specifically fresh mafic rock, to build the pavement of mine roads is already common in this sector. Reducing the movement of this material is important for reducing environmental impacts because it reduces the need for locations to set up new waste piles.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

Akbulut, H., & Gürer, C. (2007). Use of Aggregates Produced from Marble Quarry Waste in Asphalt Pavements. *Building and Environment, 42,* 1921-1930. https://doi.org/10.1016/j.buildenv.2006.03.012

Antikainen, M., & Valkokari, K. (2016). A Framework for Sustainable Circular Business Model Innovation. *Technology Innovation Management Review, 6,* 5-12. https://doi.org/10.22215/timreview/1000

Aragão, G. A. S. (2008). *Classificação de pilhas de estéril na mineração de ferro.* Dissertação de mestrado, Universidade Federal de Ouro Preto. https://www.repositorio.ufop.br/server/api/core/bitstreams/3351fe58-0b1e-41a4-a4e8-4e620836fd1c/content

Benarchid, Y., Taha, Y., Argane, R., & Benzaazoua, M. (2018). Application of Quebec Recycling Guidelines to Assess the Use Feasibility of Waste Rocks as Construction Aggregates. *Resources Policy, 59,* 68-76. https://doi.org/10.1016/j.resourpol.2018.01.004

Campos, V., & Peroni, R. (2023). Incorporating Value to Waste Rock in the Ultimate Pit Optimization for Haul Road and Mining Pads Construction and Maintenance Purposes. In *Applications and Opportunities in Mining Conference (APCOM).* Society for Mining, Metallurgy & Exploration (SME).

Carneiro, J. P. G., & Mendes, M. V. A. (2024). Technical Feasibility Analysis of the Incorporation of Material Previously Classified as Sterile in a Beneficiation Plant. *Revista Foco, 17,* e4805. https://doi.org/10.54751/revistafoco.v17n4-026

Castro-Gomes, J. P., Silva, A. M. P., Peralbo, C. R., & Suarez, J. A. D. (2011). Recycled Materials for Technical Artistic Applications Obtained with Tungsten Mine Coarse Wastes. In *COST C25, International Conference on Sustainability of Constructions, towards a Better Built Environment.* University of Malta.

Coulomb, C. A. (1776). Essai sur une application des regles de maximis et minimis quelques problemes de statique, relatits a l'architecture. *Memoires de Mathematique de l'Academie Royale de Science, 7,* 343-387.

El Machi, A., & Hakkou, R. (2024). Implementation of Circular Economy between Mining and Construction Sectors: A Promising Route to Achieve Sustainable Development Goals. In A. Bahrami (Ed.), *Sustainable Structures and Buildings* (pp. 51-63). Springer International Publishing. https://doi.org/10.1007/978-3-031-46688-5_4

Gomes, A. C. F. (2017). *Estudo de aproveitamento de rejeito de mineração.* Dissertação de Mestrado, Universidade Federal de Minas Gerais. https://repositorio.ufmg.br/bitstream/1843/BUOS-AN9QQC/1/anacl_udiagomes_disserta__ofinal.pdf

Gontijo, M. D. (2021). Manuseio e aproveitamento de estéreis em mineração. *Revista Engenharia de Interesse Social, 6,* 104-116. https://doi.org/10.36704/25256041/reis.v6i8.6005

Hebhoub, H., Aoun, H., Belachia, M., Houari, H., & Ghorbel, E. (2011). Use of Waste Marble Aggregates in Concrete. *Construction and Building Materials, 25,* 1167-1171. https://doi.org/10.1016/j.conbuildmat.2010.09.037

Hoek, E. (2007). *Practical Rock Engineering.* Evert Hoek Consulting Engineer, Inc.

Hoek, E., Carranza-Torres, C., & Corkum, B. (2002). Hoek-Brown Failure Criterion-2002 Edition. *Proceedings of NARMS-Tac, 1,* 267-273.

ICMM (2017). *The "Circular Economy" in Mining and Metals.* https://www.icmm.com/en-gb/case-studies/2017/mining-minerals/circular-economy

Jose, S. A., Calhoun, J., Renteria, O. B., Mercado, P., Nakajima, S., Hope, C. N. et al. (2024). Promoting a Circular Economy in Mining Practices. *Sustainability, 16,* Article No. 11016. https://doi.org/10.3390/su162411016

Kaufmann, W. W., & Ault, J. C. (1977). *Design of Surface Mine Haulage Roads*.

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the Circular Economy: An Analysis of 114 Definitions. *Resources, Conservation and Recycling, 127,* 221-232. https://doi.org/10.1016/j.resconrec.2017.09.005

Lébre, É., Corder, G., & Golev, A. (2017). The Role of the Mining Industry in a Circular Economy: A Framework for Resource Management at the Mine Site Level. *Journal of Industrial Ecology, 21,* 662-672. https://doi.org/10.1111/jiec.12596

MMA—Ministério do Meio Ambiente (2009). *Agenda ambiental na administração pública* (5ª ed., revista e atualizada). Ministério do Meio Ambiente. https://www.cuiaba.mt.gov.br/upload/arquivo/cartilha_a3p_36.pdf

Mohr, O. (1900). Welche Umstande bedingen die Elastizitatsgrenze und den Bruch eines Materials? *Zeitschrift des Vereins Deutscher Ingenieure Band, 44,* 1524-1530.

Mun, K. J., Choi, N. W., So, S. Y., & Soh, Y. S. (2007). Influence of Fine Tailings on Polyester Mortar Properties. *Construction and Building Materials, 21,* 1335-1341. https://doi.org/10.1016/j.conbuildmat.2005.12.021

Raupp-Pereira, F., Ball, R. J., Rocha, J., Labrincha, J. A., & Allen, G. C. (2008). New Waste Based Clinkers: Belite and Lime Formulations. *Cement and Concrete Research, 38,* 511-521. https://doi.org/10.1016/j.cemconres.2007.11.008

Read, J., & Stacey, P. (2009) *Guidelines for Open Pit Slope Design*. CSIRO Publishing.

Ritzén, S., & Sandström, G. Ö. (2017). Barriers to the Circular Economy—Integration of Perspectives and Domains. *Procedia CIRP, 64,* 7-12. https://doi.org/10.1016/j.procir.2017.03.005

Robertson, A. M. (1987). Mine Waste Disposal: An Update on Geotechnical and Geohydrological Aspects. In D. J. A. VanZyl, J. D. Nelson, S. R. Abt, & T. A. Shepherd (Eds.), *Geotechnical and Geohydrological Aspects of Waste Management* (pp. 123-130). Taylor & Francis.

Swan, G., & Sepulveda, R. (2001). Slope Stability at Collahausi. In W. A. Hustrulid, M. K. McCarter, & D. J. A. Van Zyl (Eds.), *Slope Stability in Surface Mining* (pp. 163-170). SME, Inc.

Thompson, R. J., Peroni, R. L., & Visser, A. T. (2019). *Mining Haul Roads: Theory and Practice*. CRC Press/Balkema.

Yellishetty, M., Karpe, V., Reddy, E. H., Subhash, K. N., & Ranjith, P. G. (2008). Reuse of Iron Ore Mineral Wastes in Civil Engineering Constructions: A Case Study. *Resources, Conservation and Recycling, 52,* 1283-1289. https://doi.org/10.1016/j.resconrec.2008.07.007

Young, A., Barreto, M. L., & Chovan, K. (2021). *Towards a Circular Economy Approach to Mining Operations: Key Concepts, Drivers and Opportunities*. Enviro Integration Strategies Inc./MERG.