Balancing Economic Viability and Environmental Stewardship in Open-Pit Mining: A Multi-Objective Optimization Approach

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ABSTRACT

The quest for sustainable development in the mining sector is more pressing than ever, as the industry grapples with the dual challenges of satisfying the global thirst for minerals and mitigating its environmental footprint. This paper introduces a transformative multi-objective optimization (MOO) framework that can balance the economic and environmental aspects of open-pit mining, with a focus on greenhouse gas (GHG) emissions. A case study on an open-pit iron ore mine in the Middle East validates the framework's efficacy. The results demonstrate the potential for significant GHG emission reductions with minimal impact on economic returns. Through comprehensive scenario analysis, we illustrate the trade-offs and synergies between maximizing NPV and minimizing ecological costs. Our findings underscore the importance of integrating environmental considerations into mine planning to foster a sustainable and economically viable mining industry. The proposed MOO framework serves as a blueprint for sustainable practices, ensuring the resilience of the mining sector and its commitment to the planet's future.

1. Introduction

Open-pit mining has been significant in the global extraction of minerals and now stands at a turning moment where the need for sustainable growth is critical. It reconciles the economic imperatives of resource extraction with the moral and ecological imperatives of preserving the environment. This is a paradigm shift from the old ways of mining, which often result in great environmental degeneration to the practices that will sustain the industry and ecological wholeness. With sustainability, open-pit mining can cut its use of energy and consequent emissions, hence contributing to the wellness of the planet without compromising economic growth and development [1, 2].

Environmental stewardship integrated with economic efficiency forms the backbone of modern open-pit mining operations, striving toward a harmonious balance between resource extraction and ecological preservation [3]. This sustainable approach requires comprehensive strategies to be in place that address the most pressing environmental concerns: habitat destruction, water pollution, and soil erosion, while optimizing the economic yield [4]. Mine planning plays an important role in this regard as a strategic tool that lays out mining activities in direct alignment with environmental and economic objectives [5-8]. Weaving environmental considerations into the very fabric of mining operations means that, beyond mere compliance with regulations, it enables the sector to

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invest in a business model that will improve its social license to operate and contribute to long-term profitability. In all, there exists no trade-off between economic and environmental imperatives but rather a synergistic integration, and this is where effective mine planning acts as the blueprint for sustainable practices that ensure the industry's resilience and commitment to the future of the planet [9].

The essence of implementing a multi-objective approach to sustainable open-pit mining is effective mine planning. Planning in such activities is quite complex and includes consideration of ore body characteristics, market conditions, and environmental constraints. With sophisticated planning techniques such as computer modeling and simulation, mining engineers can foresee possible ecological effects and generate strategies to mitigate them. This kind of proactive planning ensures that mining activities are responsibly conducted, balancing economic viability with environmental stewardship, and sets the course for a more sustainable future in the mining industry [3, 10].

The integration of environmental impacts, particularly greenhouse gas (GHG) emissions, into mine planning is a critical part of research that has garnered noteworthy attention recently [2]. Munoz et al incorporated sustainability parameters directly into the ore body block model, mining projects achieved more responsible mine designs and significantly improved their sustainability performance [11]. The cradle-to-gate life cycle assessment (LCA) method was applied by Ferreira et al. for the environmental assessment of Brazilian iron ore mining. The study utilized tools such as SimaPro-7 and Ecoinvent 2.0. Grinding media were reported to have major concerns in the life cycle impacts, affecting most both human health and ecosystem quality [12]. Xu et al. developed an optimization model for open-pit production scheduling that internalizes the ecological costs, including carbon emissions and ecosystem damage, into the economic evaluation formulations. Application to a large-scale open pit mine showed that the integration of the ecological costs led to different mining sequences, lower production rates, longer mine life, and a higher overall net present value (NPV) compared to schedules that treated the ecological costs as externalities [13]. Pell et al. adopted an innovative approach to conducting LCA, which involved generating life cycle impact assessment data and creating an environmental block model of a deposit. This method incorporated spatially explicit data into long-term mine scheduling simulations, showing that significant reductions in global warming impacts can be achieved at minimal economic cost. This allows for the integration of environmental considerations into strategic mine planning [10].

Rijsdijk and Nehring conducted a scenario analysis to examine the impact of carbon pricing on the economic feasibility of a copper mine in Congo. They determined that with prices up to \$100/t, higher carbon prices will trigger a cost increment in mining and processing costs, considering both hydroelectric and coal-fired power scenarios, while showing a minor effect on cut-off grades and the optimal pit limits [14]. Agosti et al. used a novel approach to investigate the environmental and financial consequences of introducing a carbon levy in mining activities. By integrating the carbon tax directly into the resolve of the ultimate pit limit (UPL) using the new software OptimalSlope, they demonstrated that relationships between carbon tax value, carbon emissions, ore extracted, and NPV exhibit linearity, and that geotechnically optimal pit wall profiles can result in significant economic gains without compromising safety [15]. Mirzehi et al. used an integrated LCA-MILP framework to compute the ecological effect of mining activities and incorporate these considerations into long-term open-pit mine planning. Their case study on an open-pit iron ore mine demonstrated that framework was able to lower GHG emissions by 11.05% while retaining 93.66% of the initial NPV, highlighting the potential for sustainable and economically viable mining practices [3].

This paper employs a multi-objective optimization (MOO) framework to achieve the goal of balancing economic viability with environmental stewardship by internalizing ecological costs in long-term mine planning. First, the ecological costs of open-pit mining, including carbon emission costs associated with energy consumption, are quantified. Different scenarios are then defined by assigning various weights to each objective. Finally, a case study on an open-pit mine is presented to compare the mine planning outcomes across these scenarios, demonstrating the framework's effectiveness in achieving a sustainable balance.

2. Material and Methods

In this research, we develop a comprehensive multi-objective framework for long-term planning in sustainable open-pit mining. This approach harmonizes economic viability with environmental stewardship, ensuring that both financial returns and ecological costs are considered during the mine's lifecycle. The framework incorporates carbon pricing into the decision-making procedure, accounting for carbon emissions from all mining activities, including beneficiation and mining and transportation activities. Advanced techniques are employed for assessing options in such a way that NPV is maximized, while minimizing ecological costs. The effectiveness of this integrated framework was confirmed through a case study conducted on an open-pit iron mine located in the Middle East. Moreover, the methodology integrates LCA and quantifies greenhouse gas emissions to conduct a comprehensive evaluation of environmental impacts. This approach ultimately helps to steer mining operations towards sustainability and economic viability.

2.1. Multiple Objective Model for Long-term Planning

Studies highlight the importance of incorporating ecological costs into mine design to mitigate environmental impacts. Optimal carbon emission management across key mining processes—including beneficiation, mining, and transportation—is crucial for achieving carbon peak goals and effectively managing emissions. Moreover, optimal selection of sustainable development strategies for open pit mining enterprises is critical to long-term profits and environmental sustenance [16].

Therefore, we develop a multiple objective framework for sustainable long-term planning, allows for the consideration of conflicting objectives, maximizing NPV while minimizing ecological costs, leading to more comprehensive decision-making. This approach facilitates the reduction of carbon emissions in mining processes, aiding in meeting emission reduction targets and refining emission management strategies. Many mine planning approaches prioritize economic gains over environmental impacts. Our framework focuses on integrating carbon pricing into decision-making processes, ensuring that the costs of CO_2 emissions are considered at every stage of the mine's operations.

Mine planning in long-term horizon entails the strategic development and implementing of plans to optimize the value of mineral resources over their entire life cycles. This procedure considers geological, technical, economic, environmental, and social factors, as well as assessments of uncertainties and operational risks. Experts use advanced techniques such as mine life planning, simulations, optimization models, strategic options analysis, and scenario planning to evaluate and compare different decisions, aiming to identify the most suitable ones within project constraints. The significance of comprehensive mine planning lies in its crucial role in ensuring the sustainability, profitability, and safety of mining operations, while also adhering to industry regulations and standards. Table 1 outlines the indices, sets, parameters, and decision variables used to formulate this problem.

Table 1. Elements, set, variables, and parameters of the MOO framework.

Term	Description
p	Time period set, p = (0, 1, …, P)
i	Block set, i = (0, 1, …, I)
d	Block's destination set, d = (0, 1, …, D), where d=0 and d=1 denote waste and ore, respectively

I_{ri}	The precedence set of blocks that must be extracted prior to block i
T_{el}^{p}	The lowest mining capacity threshold
T_{eu}^{p}	The highest mining capacity threshold
T_{fl}^{p}	The lowest plant capacity threshold
T_{fu}^{p}	The highest plant capacity threshold
g_i	Block's grade
g_u^p	The highest-grade threshold for plant
g_l^p	The lowest-grade threshold for plant
b_i	Block's tonnage
V_i	Economic value of block i
C_i	Ecological costs of block i
ε	Discount rate

2.1.1. Objective Function

The model includes two distinct objectives: the first aims to maximize the NPV of the mining operation (Eq. (1)), while the second aims to minimize the total ecological costs associated with CO_2 emissions from energy consumption (Eq. (2)). In addressing the mine planning problem, our focus is on maximizing economic benefits while simultaneously minimizing environmental impact, specifically in terms of carbon emissions. This unique approach integrates environmental concerns as crucial elements in the optimization process, leading to a thorough assessment of mining strategies that strike a balance between economic feasibility and ecological sustainability. The result is a well-optimized long-term mine plan that not only maximizes economic gains but also proactively tackles environmental issues, showcasing a progressive outlook towards mining operations [3, 17].

$$Max \sum_{d=1}^{D}\sum_{p=1}^{P}\sum_{i=1}^{I}\frac{V_i}{(1+\varepsilon)^p}x_{id}^{p}b_i, \qquad x_{id}^{p}\epsilon\{0,1\} \tag{1}$$

$$Min \sum_{d=1}^{D}\sum_{p=1}^{P}\sum_{i=1}^{I}\frac{C_i}{(1+\varepsilon)^p}x_{id}^{p}b_i, \qquad x_{id}^{p}\epsilon\{0,1\} \tag{2}$$

The objectives in the problem vary in scale and impact on the system. Additionally, the second objective aims to minimize deviation from a target value. To address this, the authors utilized the normalization approach, incorporating the concept of nadir and utopia points to create dimensionless objective functions [18]. This normalized model was then solved using the weighted-sum multiple-objective optimization methodology [18]. Equation (3) illustrates the function of the object representation model, which involves selecting and assigning weights to different goals to achieve desired outcomes. The terms w_1 and w_2 represent the weights assigned to each objective to prioritize and attain the desired results.

$$Objective\ =\ w_1\ \times objective\ (1) +\ w_2\ \times objective\ (2) \tag{3}$$

2.1.2. Constraints

In the mathematical modeling of goal attainment, it is essential to account for both constraints and resources. For long-term planning, models are executed with a variety of constraints, including precedence relationships, minable reserves, plant production targets, and machinery capacities. Equation (4) enforces the slope stability constraint by stipulating that if block j is necessary for extracting block i, block j must be extracted before block i to uphold the integrity of the mining structure and prevent destabilization. Equation (5) sets limits on extraction capacities, ensuring that the total tonnage of waste and ore blocks extracted does not exceed or lower than the mining extraction capacity. Equation (6) governs the input feed to the processing plant, considering the minimum and maximum processing capacities for each period. Equations (7) and (8) also set grade constraints for the processing plant to maintain the weighted average grade of the processed ore within certain limits. Moreover, Equation (9) dictates that each block can only be extracted once.

$$\sum_{d=1}^{D}\sum_{r=1}^{p} x_{id}^{p} - \sum_{d=1}^{D} x_{id}^{p} \geq 0, \quad \forall\, p = 1, \dots, P; i \in I; j \in I_{ri} \tag{4}$$

$$T_{el}^{p} \leq \sum_{d=1}^{D}\sum_{i=1}^{I} b_i\, x_{id}^{p} \leq T_{eu}^{p}, \quad \forall\ p = 1, \dots, P, d = 1, \dots, D \tag{5}$$

$$T_{fl}^{p} \leq \sum_{d=1}^{O}\sum_{i=1}^{I} b_i\, x_{id}^{p} \leq T_{fu}^{p}, \quad \forall\ p = 1, \dots, P, d = 1, \dots, D \tag{6}$$

$$\sum_{i=1}^{O} b_i\, x_{id}^{p}\left(g_i - g_u^{p}\right) \leq 0, \quad \forall\ p = 1, \dots, P, d = 1, \dots, D \tag{7}$$

$$\sum_{i=1}^{O} b_i\, x_{id}^{p}\left(g_i - g_l^{p}\right) \geq 0, \quad \forall\ p = 1, \dots, P, d = 1, \dots, D \tag{8}$$

$$\sum_{d=1}^{D}\sum_{p=1}^{P} x_{id}^{p} \leq 1, \quad \forall\, i = 1, \dots, I \tag{9}$$

2.2. Emission Quantification and Pricing

The mining process incurs high energy consumption and carbon emissions mainly due to operational costs associated with activities like drilling, blasting, loading, hauling, ancillary tasks, and crushing.

Our first step was to evaluate the energy consumption of individual blocks by considering the relevant physical processes, as outlined by Muñoz et al. [11] and Rijsdijk and Nehring [14]. This was followed by calculating the global-warming potential (GWP) based on the estimated energy consumption. Energy consumption and carbon emissions are crucial factors in the advancement of mining projects due to their high energy intensity. The calculation of energy consumption for each block depends on the specific unit processes that impact it.

The formulas used in this study are based on the methodology outlined by Muñoz et al. [11] and NPI [23] for calculating emissions from equipment, diesel, and electricity consumption. For a detailed explanation of how the environmental impact of the mining operation is quantified, please refer to Table 2. The equations in Table 2 consider specific emission factors and operational parameters relevant to this study. All variables, except for the block's physical properties, were kept constant, including environmental conditions and machinery used. Diesel equipment was chosen in accordance with regional regulations, unless otherwise specified.

Table 2. Equations for calculating GWP in mining operations.

Operation	Equation	Detail
Drilling	$C_{drilling}\left[\frac{kg_{CO2e}}{t}\right] = \frac{A \times E_v \times L \times N}{\eta_{drill} \times m_b} \times (\alpha + \beta)$	A: The area of the drill hole L: The charged length of the drill hole N: The number of drill holes for each block E_v: The drilling specific energy that depends on rock type η_{drill}: The assumed driller efficiency m_b: The mass of the block in ton α, β: The coefficient of carbonization for diesel, electrical power matrix
Blasting	$C_{blasting}\left[\frac{kg_{CO2eq}}{t}\right] = LF \times E_{expl} \times \delta$	LF: The load factor, defined as the amount of explosive per ton of detonated rock E_{expl}: The specific explosive energy δ: The coefficient of carbonization for explosive
Loading	$C_{loading}\left[\frac{kg_{CO2eq}}{t}\right] = \frac{P_L \times T}{\eta_{loader} \times m_{truck}} \times (\alpha + \beta)$	P_L: The front loader power T: The assumed average time to meet the loading capacity of the dumper η_{loader}: The assumed front loader efficiency m_{truck}: The loading capacity of the dumper
Hauling	$C_{hauling}\left[\frac{kg_{CO2e}}{t}\right] = \frac{9.81 \times S \times (m_{truck} \times z + (R_s + R_i) \times (2 \times M_{truck} - m_{truck}))}{m_{truck}} \times (\alpha + \beta)$	S_i: The distance of the ith block to destination z: The inclination of the ramp R_s: The rolling resistance of the surface R_i: The assumed internal resistance of the dumper M_{truck}: The total mass of the loaded dumper
Ancillary	$C_{Ancillary}\left[\frac{kg_{CO2eq}}{t}\right] = D_a \times \alpha$	D_a: The consumption rate of diesel per ton mined

Crushing	$C_{crushing}\left[\frac{kg_{CO2eq}}{t}\right] = 3.6\times 10\ \times W_i \times \left(\frac{1}{\sqrt{P_{cr}^{80}}}-\frac{1}{\sqrt{F_{cr}^{80}}}\right)\times \zeta$	**W_i: The Bond's work index** **P_{cr}^{80}: The 80% passing sizes of the product for the crusher** **F_{cr}^{80}: The 80% passing sizes of the feed for the crusher and the mill** **ζ: The coefficient of carbonization for electrical power for comminution**

The facility under review is located in the Middle East and includes open-pit mines, a concentrator, and a hydrometallurgy plant. This study focuses on the process until the comminution of ore material, without considering downstream processes. The International Energy Agency (IEA) [24] offers a range of potential carbon prices based on country and year, as detailed in Table 3. This analysis starts with an assumed average carbon price of \$30 per ton and focuses on the Middle East, which is classified as a developing nation according to the IEA.

Table 3. USD Carbon Pricing Model [24, 25].

Cost CO2 (\$/t)	2025	2030	2040	2050
Advanced countries	75	130	205	250
Chosen developing countries and emerging markets	45	90	160	200
Other developing countries and emerging markets	3	15	35	55

2.3. Scenarios Definition

The definition of multiple scenarios is essential for assessing model performance related to multi-objective optimization. For example, by assigning different weights to each objective, one can find out how priorities change between the objectives of economic viability and environmental stewardship within the same overall mine-planning strategy. In this way, the trade-offs and synergies between maximizing the net present value and minimizing ecological costs can be examined profoundly.

Here we define eleven scenarios, each applying a different weighting of the two objectives. The first objective maximizes the NPV of the mining operation, while the last objective minimizes the total of the ecological costs associated with CO2 emissions from energy consumption. The scenarios are summarized in Table 4, indicating weights attached to each objective representing different priorities.

By systematically varying the weights assigned to each objective, we can touch base with the full range of potential outcomes, which prove very helpful when identifying optimal strategies that involve a balance between economic and environmental goals and provide insights regarding how different priorities may affect long-term mine planning decisions. Results from such scenarios will portray the flexibility and robustness of the multi-objective optimization framework in making sure that sustainable and economically viable mining operations are attained.

Table 4. Scenario definitions with varying weights for economic viability and environmental stewardship objectives.

Scenario	Symbol	Weight	
		Objective 1 (NPV)	Objective 2 (Ecological costs)
1	S1	1	0
2	S2	0.9	0.1
3	S3	0.8	0.2
4	S4	0.7	0.3
5	S5	0.6	0.4
6	S6	0.5	0.5
7	S7	0.4	0.6
8	S8	0.3	0.7
9	S9	0.2	0.8
10	S10	0.1	0.9
11	S11	0	1

2.4. Case Study

The framework was tested in a practical case study at an open-pit iron mine in Iran to evaluate its effectiveness. The reserve modeling, planning, and long-term production activities were conducted using drill-hole prospecting data. The framework includes a 10-year plan within a larger project timeline. Aerial images in Figure 3 show the location of the crusher and waste dump at the mine site.

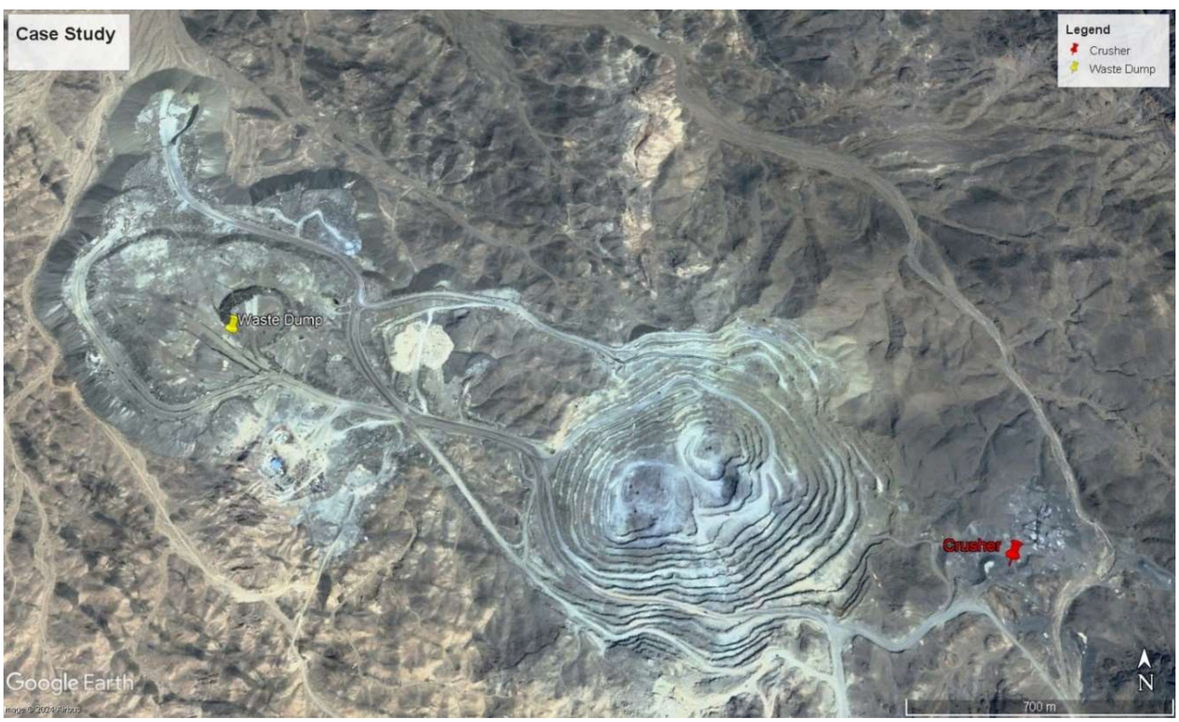

Figure 1. Aerial views of the case study area, showing the crusher and waste dump locations.

In Figure 2 a 3D depiction of the content (Fe grade) and ecological costs associated linked to various blocks within the deposit. This information was utilized to plan the pit excavation and establish the sequence of block extraction. The block model (geological) highlights high-value zones beneath the deposit, suggesting that lower-grade material should be extracted first. Blocks with high ecological costs are located to the right of the deposit, mainly due to the extra transportation required to extract them from the pit. These blocks must be transported to the waste dump where is situated on the left part.

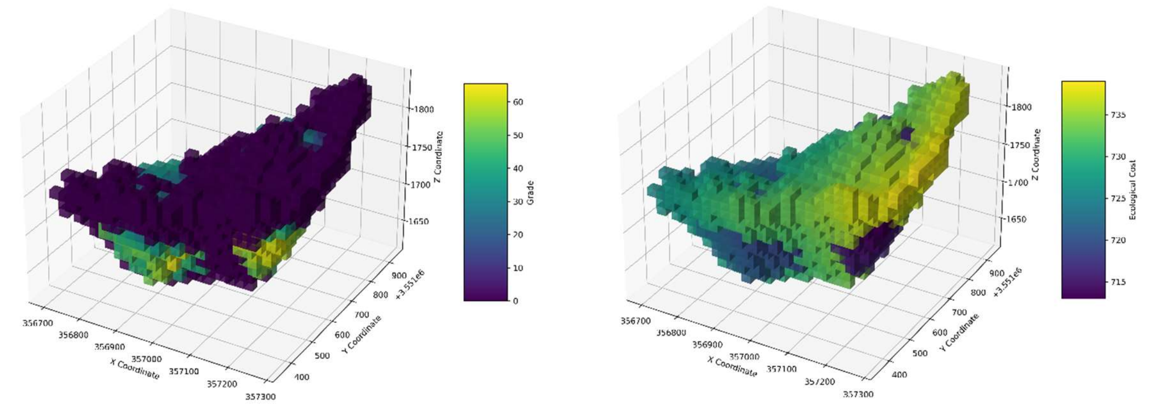

Figure 2. Distribution of grades and ecological costs across blocks.

3. Results

This section demonstrates the efficacy of MOO framework through its implementation in different scenarios. The model was created using the CPLEX® solver [26] and the Python® programming language [27]. To assess the framework's performance, we employed it in a case study focusing on an open-pit iron mine.

3.1. Economic Impacts

Economic impacts for various mining scenarios are evaluated through an analysis of the annual and cumulative NPV. The following data can be taken as examples of NPV values for ten periods for eleven different scenarios. To have a more intuitive way to show the economic impacts, Figure 3 presents the annual and cumulative NPV for each individual scenario. In this way, a visual result can show how each specific scenario impacts the global economic viability of a mining project.

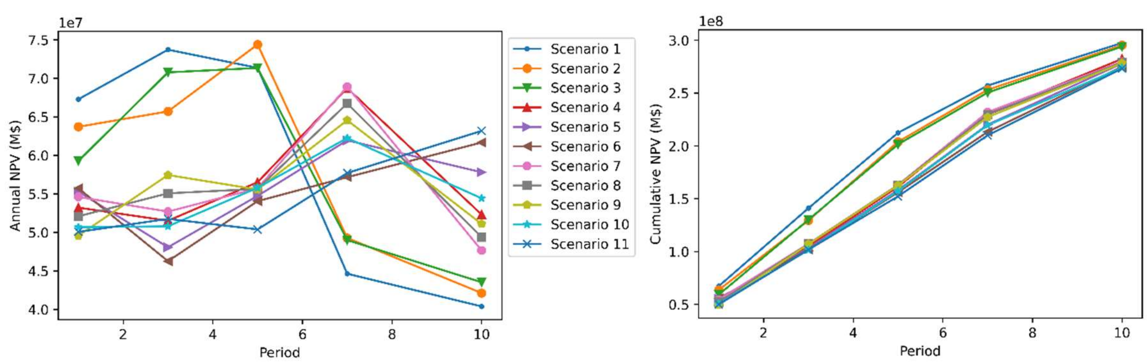

Figure 3. Annual NPV (left) and cumulative NPV (right) for scenarios.

The annual NPV data clarifies how each scenario performs economically over ten periods. High NPV scenarios, such as Scenario 1, strongly start and experience diminishing returns over time, while lower NPV and higher ecological cost scenarios, like Scenario 6, perform more steadily. This might indicate that scenarios granting more consideration to environmental cost offer more consistent return, although at a lower overall NPV. Generally, higher NPVs at the beginning show a higher cumulative NPV with benchmarks of more accentuated and profitable trajectory growth. That said, the differences between the cumulative NPVs across scenarios are not overwhelming, meaning even the lowest-ranked initial NPVs produce significant long-term profitability.

These results show the importance of scenario selection that will meet both economic and environmental objectives. Tradeoffs between short-term profit and long-term sustainability must be very well thought out. Therefore, Figure 3 reserves a graphical representation of these trends, particularly showing the effects of each scenario on overall project economic viability.

3.2. Emission Outcomes Analysis

The emission results analysis provides a broader outlook on the environmental effects of each scenario. The scenarios demonstrate how variable the focus of ecological costs affects the overall emissions. In Figure 4, detailed emission results for all scenarios are provided.

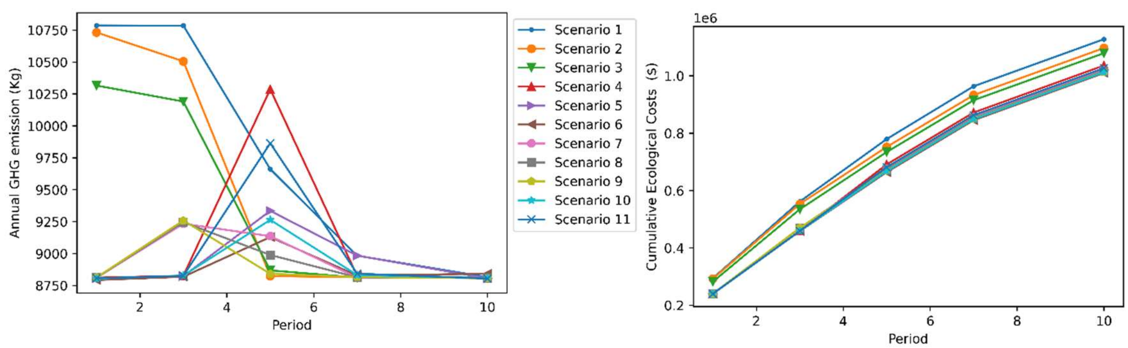

Figure 4. Annual GHG emission and cumulative ecological costs for scenarios.

The data clearly shows that GHG emissions vary across scenarios and, in most cases, are higher for corresponding to scenarios with lower ecological costs weights. Scenario 1 has the highest emission of 49,030 units and prioritizes NPV with minimum ecological costs. Scenario 6, which strikes a middle path between the two objectives, resulted in a cumulative emission of 44,410 units. Cumulative ecological cost trends involve a similar pattern as GHG, rising as priority on NPV goes up. Scenario 1 has the most significant cumulative, while Scenario 6 was more in balance. These results of this analysis underline, as far as possible, the tradeoffs between economic benefits and environment impacts, showing that a balanced development path must be sought—such that the least ecological cost is acquired at the highest level of profitability.

3.3. Block Sequencing Analysis

In this section, we examine the block sequencing variations for the different scenarios. Block sequencing is entirely important in mining operations since it affects the economic returns but also environmental costs. By examining the sequences, we can realize the optimal extraction order that allows for the maximization of NPV but also considers the impacts ecologically. To demonstrate the sequencing variations, we examined four scenarios for more significant details. Figure 5 selected scenario sequence of block extraction over ten periods indicates how the blocks are selected and extracted over time.

Earlier, it was observed that the blocks on the right side of the deposit possess lower grades and need to be transported to the waste dump on the left side. This results in higher environmental costs for these blocks. The model is designed to prioritize the extraction of lower-cost blocks in the initial stages by emphasizing the ecological cost objective, as opposed to scenarios that prioritize maximizing NPV and extracting more valuable blocks in the beginning (Figure 5).

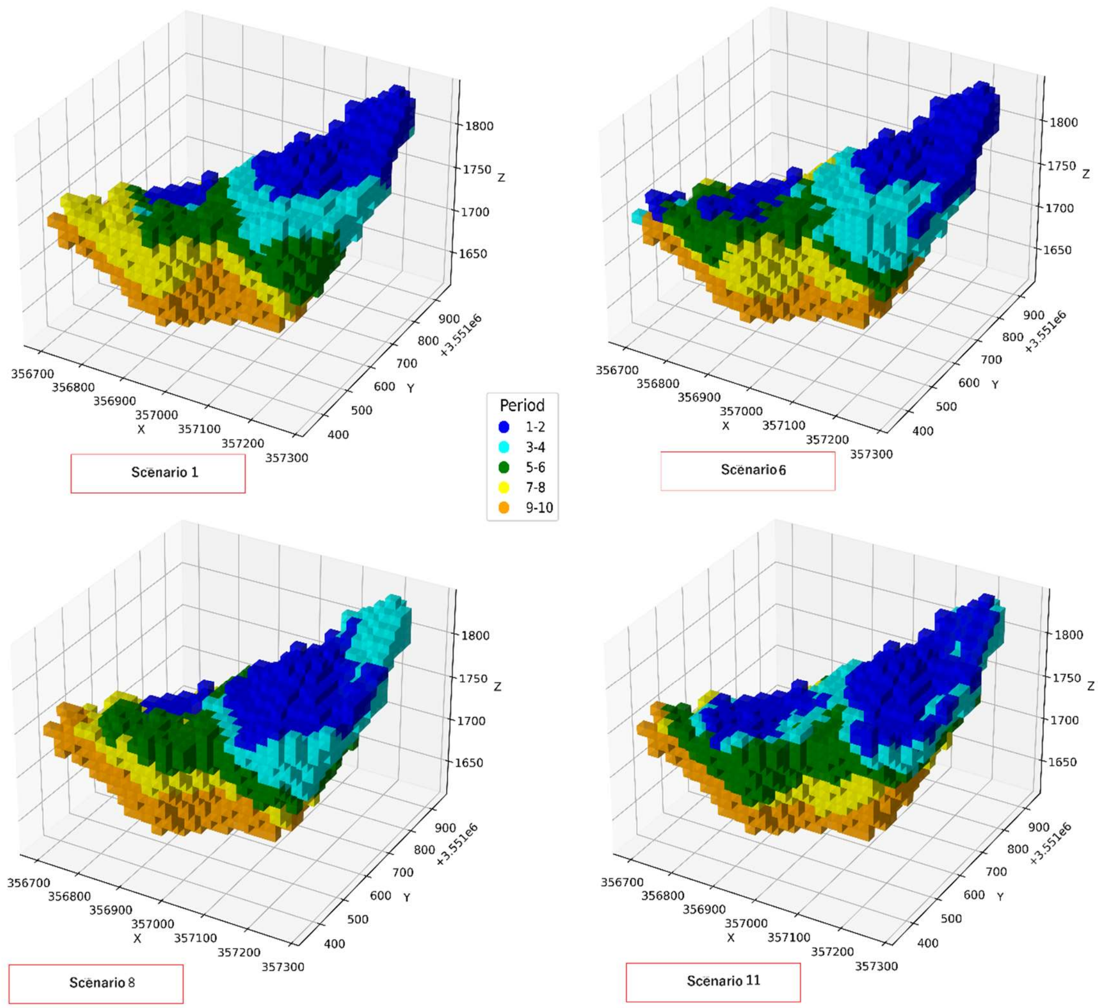

Figure 5. Block extraction sequences for selected scenarios.

3.4. Production Analysis

The production analysis offers an overview of each period's allocation of ore and waste blocks across different scenarios. The analysis highlights the impact of prioritizing economic versus ecological objectives on production levels and financial returns. Figure 6 provides detailed production outcomes for all scenarios.

Based on Figure 6, all scenarios with higher weights of economic elements depict relatively high constant production in the early periods but decrease slightly during the latter periods. The decline of economic priorities sees scenarios with high production but great fluctuation, especially during the middle periods. Scenarios 4, 5, and 6 remain balanced with as constant a level of production as possible to meet the minimum requirements of the plant. Finally, high-ecological-weight scenarios such as 10 and 11, maintaining the lowest plant requirement, vary very little in their production levels. Generally, all scenarios can work on the assurance of the minimum requirements for the plant, opening the possibility of balancing interests between the economic and ecological perspectives.

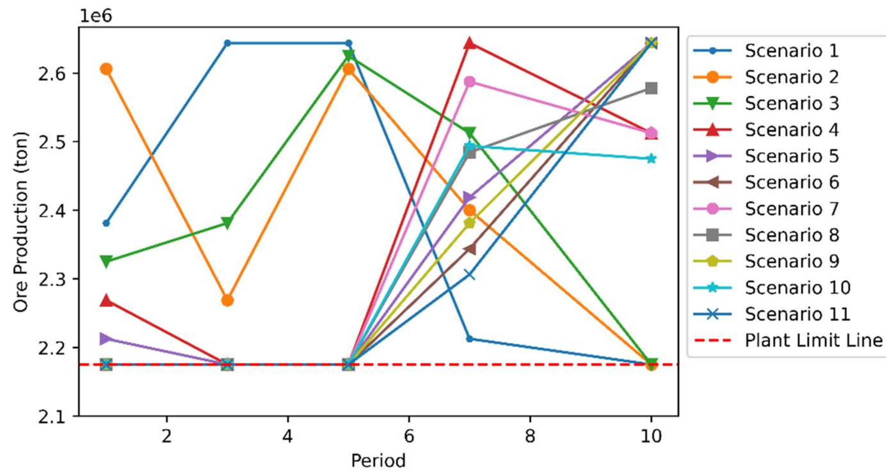

Figure 6. Annual ore production with lower threshold of plant.

3.5. Stripping Ratio (SR) Analysis

The stripping ratio (SR) is a crucial factor in mine design and planning, impacting resource utilization and operational efficiency. Figure 7 shows the annual stripping ratios for different scenarios. Firstly, high SR values obtained for the scenarios mean that a considerable amount of waste is removed relative to ore extraction. Scenario 1, for example, starts with an SR of 2.496, decreasing to 1.830 before rising again slightly. This pattern of high initial SR values, followed by a reduction, is common in the early scenarios, which are focused more on economic goals, and probably this reflects an initial phase of considerable overburden removal to access the ore. Moving to the later scenarios, with a greater emphasis on ecological goals—scenarios 10 and 11—the trend of the SR values is more modest and less variable.

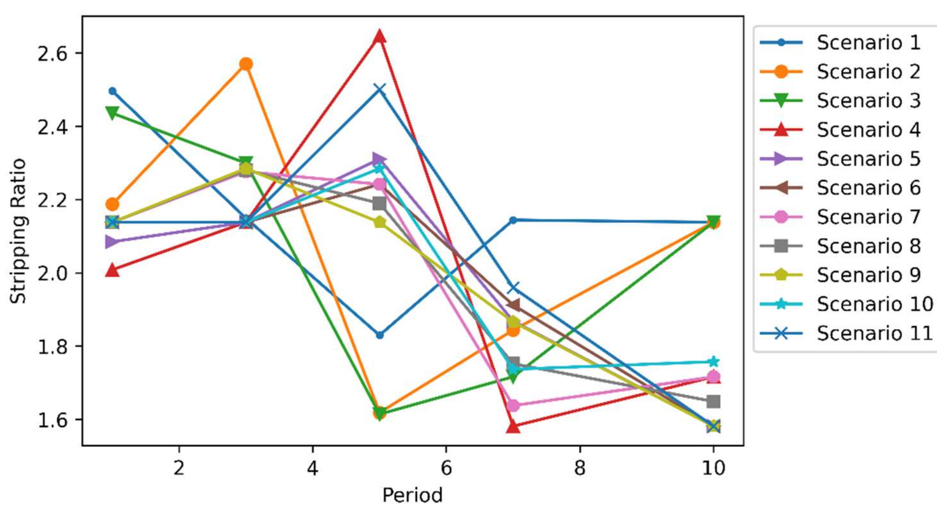

Figure 7. Stripping ratio analysis for scenarios over time.

Overall, the change from scenarios with high economic weight to scenarios with high ecological weight bolds a shift toward more balanced and efficient mining operations. High SR values initially depict a function of significant promotion to access ore bodies, while for the later scenarios, these will be optimized, with more consistent and manageable SRs within targets keeping output while minimizing environmental impact and operational costs is the objective.

Table 5 provides an overview of the outcomes from the MOO framework for various scenarios, including CO_{2eq} emissions, NPV, environmental costs, and SR. Furthermore, Table 5 highlights the variations in outcomes across different scenarios.

Table 5. Results of integrated framework in two scenarios.

Scenario	Ore (Mt)	Waste (Mt)	SR	GHG (Kg)	Eco cost (M$)	NPV (M$)
Scenario 1	12.06	25.86	2.14	49030	1.13	297.37
Scenario 2	12.06	24.83	2.06	47688	1.10	295.19
Scenario 3	12.02	24.34	2.02	46999	1.08	293.91
Scenario 4	11.78	23.46	1.99	45553	1.04	282.27
Scenario 5	11.63	22.99	1.98	44753	1.02	277.84
Scenario 6	11.51	22.84	1.98	44409	1.01	274.87
Scenario 7	11.63	23.03	1.98	44802	1.02	279.57
Scenario 8	11.59	22.96	1.98	44668	1.02	278.90
Scenario 9	11.55	22.89	1.98	44535	1.01	278.23
Scenario 10	11.49	22.95	2.00	44535	1.01	273.91
Scenario 11	11.46	23.44	2.04	45142	1.02	273.08

4. Conclusion

This paper addresses the critical requirements of sustainability practices in open-pit mining through the development of a multi-objective optimization framework that balances the economic and environmental goals. An open-pit mine in the Middle East has been tested to prove this proposed framework, proves its ability at harmonizing economic viability and ecological stewardship. Results indicate that while increasing importance given to economic-oriented objectives increases the initial NPV, it significantly increases the long-term variability of profitability for a mine. Conversely, high-ecological-weight positioning scenarios ensure more stable economic returns, besides effectively reducing GHG emissions. Block sequencing and production analyses further reiterate the framework's ability in optimum resource extraction, besides maintaining stable production levels with reduced environmental impacts. Stripping ratio analysis confirms the efficiency of the framework in managing overburden removal and ensures sustainable utilization of resources. Overall, this research emphasizes the significance of environmental considerations into mine planning that will lead toward economic success and sustainability.

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