Sustainable Mine Planning: An Integrated Framework for Balancing Economic and Environmental Costs in Open-Pit Mining

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ABSTRACT

As global demand for mineral resources grows, the mining sector faces increased scrutiny over its environmental impact, necessitating a shift towards sustainable practices. This research presents an innovative framework for long-term open-pit mine planning that integrates economic and environmental considerations. By incorporating carbon pricing into the decision-making process, the framework addresses financial risks and introduces two scenarios: one focused on minimizing environmental costs and the other on maximizing adjusted Net Present Value (NPV). Applied to an open-pit iron ore mine in the Middle East, the framework's impact on block sequencing, greenhouse gas emissions, and financial outcomes was evaluated. The minimization scenario achieved 90.54% of the global warming impact and 90.48% of environmental costs while maintaining 96.25% of the adjusted NPV compared to the maximization scenario. Sensitivity analyses highlighted the framework's adaptability to varying carbon pricing scenarios. This research offers a sustainable approach to mine planning, balancing economic returns with ecological responsibility, and provides valuable insights for decision-makers in the mining industry.

1. Introduction

Mining industries contribute substantial economic and societal advantages to a nation by providing essential raw materials for both domestic and global industries, fostering infrastructure development, and generating employment opportunities and revenue for the local community [1, 2]. While the mining industry significantly contributes to economic and societal aspects, which are essential pillars of sustainable development, it also harbors potential adverse effects on the environment, representing the third crucial facet of sustainability [3]. The adverse environmental effects of the mining industry encompass the depletion of natural habitats, contamination of water and air, and the displacement of indigenous communities [4]. Achieving sustainable development in the mining sector necessitates striking a harmonious balance among economic advancement, as well as environmental and social preservation [5, 6].

Mine planning is a part of process design in mining, and it allows for the use of eco-design principles in the strategic decision-making stage. Mine planning in general and long-term production scheduling in particular, involve the selection of specific materials for extraction and determining the sequence and timing of extraction to minimize costs or achieve a particular

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business objective. This procedure can take place long before operations commence and can be revised throughout the mine's lifespan. Typically, the process entails collecting geological data through methods such as drill holes or other sampling techniques. Using this information, it is possible to construct a block model that includes details about the position and mineral composition of the deposit. The selection of ore and waste is determined by their economic value, and their arrangement is planned to guarantee a consistent marketable grade for the products [7-14].

In recent years, the prime focus of research on the production scheduling problem has been to minimize the scale of problem and account for uncertainties [7, 15-20]. The initial objective is to enhance the efficiency and practicality of the optimization algorithm, while the secondary goal is to achieve the highest degree of stability between investment return and risk. Also, the primary objective function of production scheduling optimization consistently revolves around maximizing economic benefit. Unfortunately, environmental concerns closely tied to production scheduling have garnered less attention in this context.

Previous studies have addressed the environmental impacts of mining in mine design or planning, particularly greenhouse gas (GHG) emissions, through two main approaches: 1) quantification, applied as constraints, and 2) incorporation into economic parameters through taxes or costs. For the first category, Chaulya [21] utilized a unique methodology, conducting site visits to three iron ore mines to quantify rates of particulate emissions and derive equations for different surface activities. The emission rates during mining activities are subject to influence from the physical properties of the ore. Muñoz, Guzmán [22] introduced an approach to estimate comparable carbon emissions and energy consumption resulting from key mining activities at the Block Model (BM) level. They proposed a new method that involves incorporating a carbon tax, proportionate to the emitted amount, as supplementary costs for each block within the mine BM. This cost accounts for the emissions generated by all emitting mining activities. Pell, Tijsseling [23] introduced an innovative approach to Life Cycle Assessments (LCA) by generating spatially explicit data for environmental impact modeling in mining projects. The findings demonstrate substantial reductions in global warming impact with minimal economic costs, emphasizing the potential of incorporating environmental constraints in strategic mine planning.

Limited research exists in the public domain that evaluates the technical and economic implications of integrating a carbon price into the operations of resource projects. Liu, Ren [24] explores the impact of carbon pricing on an iron ore mine, specifically examining whether transitioning from open-pit to underground operations can mitigate the effects of a carbon price. Rijsdijk and Nehring [25] examine the economic consequences of carbon pricing on a copper-cobalt mine in the Democratic Republic of Congo, revealing that a $30/t carbon price moderately impacts mining and processing costs. The study emphasizes the intricate relationship between carbon pricing, operational expenses, and the economic feasibility of mining operations. Agosti, Utili [26] pioneer a simultaneous incorporation of carbon tax in Ultimate Pit Limit (UPL) determination, exploring its impact on Net Present Value (NPV), ore extraction, and carbon emissions. Examining the Marvin copper deposit, the research advocates for optimal pit wall profiles, showcasing substantial gains of up to 215 million AUD without compromising safety.

The correlation between mining plans and the environmental impacts on a particular mining project is evident. Nevertheless, as outlined earlier, conventional open-pit mine planning continues to prioritize maximizing economic gains as the primary objective, neglecting the ecological expenses incurred through resource extraction. Simultaneously, mining operations do not account for the environmental repercussions they generate. While the laws in numerous countries mandate environmental assessments for mining projects, there persists a degree of autonomy in mine design.

This paper introduces an innovative integrated framework that incorporates the minimization of environmental costs, specifically Global Warming Potential (GWP), into strategic mine planning, diverging from conventional approaches. So, this paper quantifies the environmental costs of open-pit mining and incorporates such costs in a mine plan optimization model to demonstrate the influence of environmental costs on the outcomes. Furthermore, a model emphasizing NPV maximization that accommodates environmental costs was developed for comparative analysis of results. This study employs a case analysis of an iron ore deposit situated in the Middle East to evaluate the impact of the integrated framework on an operational site. Considering the widespread adoption of carbon pricing as a significant environmental concern in various global jurisdictions, it is crucial to quantify the economic implications of a harmful environmental pollutant for long-term strategic optimization.

2. Material and Methods

This study began by assessing the energy consumption and measuring greenhouse gas emissions in open-pit mining activities, using recent researches. Our analysis included drilling, blasting, loading, hauling, ancillary tasks, and crushing, taking into account factors such as drill meters, explosive usage, and diesel consumption. A crucial step involved integrating carbon pricing into our analysis, accounting for potential financial risks. We adopted a unique approach, distinguishing emissions based on block destinations. To ensure a comprehensive understanding of the environmental impact, we developed an integrated framework for long-term mine planning, addressing economic and ecological considerations. This framework introduced innovative strategies, such as minimizing environmental costs and maximizing adjusted NPV. The integrated framework captures the complex relationship between economic value and associated carbon costs. To visually illustrate our methodology, we propose a flowchart (Figure 1) that outlines the sequential steps, starting from quantifying emissions to implementing the integrated framework for long-term mine planning.

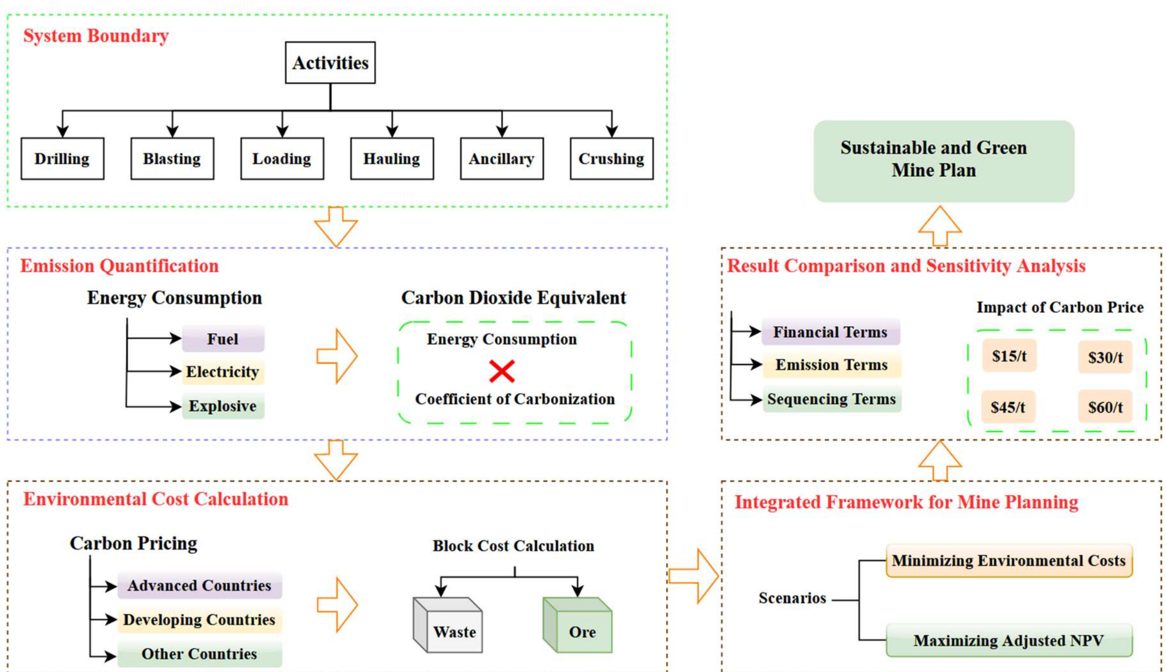

Figure 1. Sequential step of novel integrated framework.

2.1. Emission Quantification

In recent years, there have been a handful of studies focusing on conducting life cycle assessments, quantifying greenhouse gas emissions, and exploring carbon tax and pricing within the operational context of open-pit mines [22, 23, 25-27].

Energy consumption and carbon emissions in the mining process are primarily driven by operational expenditures such as drilling, blasting, loading, hauling, ancillary activities, and crushing. In alignment with Muñoz, Guzmán [22] and Rijsdijk and Nehring [25], our initial step involved assessing the energy consumption of individual blocks by considering the relevant physical processes, followed by the calculation of the global-warming potential (GWP) derived from the estimated energy consumption.

Table 1. The utilized attributes in equations [22, 23, 25-27].

Attribute	Description	value	Attribute	Description	value
$\boldsymbol{R_d}$	The hourly rate of diesel consumption during drilling	40 l/hr.	D_l	The consumption rete of diesel per ton mined	0.18 l/ton
$\boldsymbol{M_d}$	Drill meters needed per ton of mined rock	0.0085 m	S	The distance of block from destination	km
$\boldsymbol{B_F}$	The percentage of mined rock that necessitates drilling and blasting	100%	ζ	Carbonization's coefficient of electrical power	0.56kgCO_{2eq}/MJ
$\boldsymbol{T_A}$	The amount of material extracted	ton	r	The slope of the ramp	10%
$\boldsymbol{P_r}$	The speed at which the drill penetrates	33 m/hr.	R_s	The frictional resistance of the surface	2%
$\boldsymbol{Q_f}$	The amount of CO_{2eq} generated from diesel combustion	2.64 kgCO_{2e}/l	R_i	The estimated internal resistance of the truck	1%
$\boldsymbol{P_F}$	The powder factor needed for the block	0.56 kg/m^3	M_{truck}	The overall weight of the loaded truck	166ton
$\boldsymbol{\rho}$	Density	3 kg/m^3	δ	Carbonization's coefficient	0.61kgCO2e/MJ
$\boldsymbol{R_{ANFO}}$	The proportion of ANFO in the explosive blend	66%	D_a	The consumption rete of diesel per ton mined	0.26 l/ton
$\boldsymbol{Q_A}$	The amount of CO_{2e} generated from ANFO combustion	0.18kg	W_i	The Bond's grindability index	17.325 kWh
$\boldsymbol{R_{Emulsion}}$	The proportion of emulsion in the explosive blend	34%	P_{cr}^{80}	The product sizes where 80% of the material through for the crusher	15 × 103 μm
$\boldsymbol{Q_E}$	The amount of CO_{2e} generated from emulsion combustion	0.137kg	F_{cr}^{80}	The product sizes where 80% of feed material through for the crusher	75 × 103 μm
$\boldsymbol{m_{truck}}$	The truck's loading capacity	92.2ton			

Energy consumption and carbon emission play pivotal roles in the progression of mining projects, given their significant intensity in energy terms. Simultaneously, carbon emission stands out as a critical factor in the realm of sustainability. The determination of energy consumption for each block is contingent upon the unit processes influencing it [22]. The subsequent section outlines the equations employed to compute carbon emissions associated with each activity that contributes to carbon production. Table 1 contains all the required attributes for the equations are presented.

2.1.1. Drilling and Blasting

The initial mining activity involves drilling and blasting, which aims to fragment the rock for subsequent excavation and transportation. The activities of drilling and blasting can have an impact on subsequent processes, potentially reducing the energy demand during the crushing and milling phases. Emissions generated during drilling and blasting activities stem from diesel consumption in mechanical drilling and the release of gases resulting from blasting, which involves the use of ammonium nitrate/fuel oil (ANFO) consisting of 94% ammonium nitrate and 6% diesel.

The term "CO2eq" or "Carbon dioxide equivalent" is employed to characterize various greenhouse gases, providing a means to aggregate the overall impact of all gases produced during blasting activities. This paper excludes non-carbon-based gases from consideration, given their negligible quantities.

Equation 1 represents the amount of CO2eq generated from diesel consumption during the drilling process [25]. This equation considers the meters drilled, patterns drilled, and tons mined.

$$C_{Drill} = R_d \times \frac{M_d \times B_F \times T_A}{P_r} \times Q_f \tag{1}$$

The amount of CO2e generated from blasting activities is expressed in Equation 2 [25]. A combination of ANFO and emulsion is employed in the operation, with the proportion of each varying seasonally depending on whether it is the wet or dry season. The powder factor serves as a variable parameter determined by lithology and weathering, applied individually to each block. This equation relies on the consumption of explosives, the number of loaded holes, and the quantity of material mined.

$$C_{Blast} = \left(T_A \times \frac{P_F}{\rho}\right) \times \left((R_{ANFO} \times Q_A) + (R_{Emulsion} \times Q_E)\right) \tag{2}$$

2.1.2. Loading

Equation 3 represents the CO_{2eq} emissions resulting from diesel consumption during the loading process, where the loading fleet is predominantly powered by diesel.

$$C_{Loading} = T_A \times D_l \times Q_f \tag{3}$$

2.1.3. Hauling

Haulage pertains to the transportation of material from the pit to destinations such as crushers, waste rock dumps, or stockpiles. The energy required to transport one ton of material, and the associated diesel consumption vary based on factors such as the depth of material extraction, the positioning of long-term stockpiles and waste dumps, and the type of ramp system employed. Hence, Equation (4) can be employed to calculate the CO_{2eq} emissions and the specific energy required for transporting one ton of material from the pit to either the processing plant or the waste dump. The determination of the distance of the *i*th block from the comminution plant or waste dump relies on case study and the location of destinations.

$$C_{Hauling} = Specific\ Energy \times carbonization's\ coefficient = \tag{4}$$

$$\left(\frac{9.81 \times S \times \left(m_{truck} \times r + (R_s + R_i) \times (2 \times M_{truck} - m_{truck})\right)}{m_{truck}}\right) \times \delta$$

2.1.4. Ancillary

An ancillary fleet, comprising front-end loaders, graders, bulldozers, fuel trucks, and excavators with a capacity of less than 300 tons (secondary loading units), is employed for tasks such as bench preparation, maintenance of haul roads, reclamation of stockpiles, rehabilitation of waste dumps, and various other activities. The CO_{2eq} emissions resulting from diesel consumption in ancillary activities can be represented by Equation 5, which translates ancillary activities and their respective diesel consumption into an equivalent ton mined.

$$C_{Ancillary} = T_A \times D_a \times Q_f \tag{5}$$

2.1.5. Crushing

The comminution stage, where solid materials are reduced from one average particle size to a smaller size through crushing methods, is exclusively carried out on mined material categorized as ore. Hence, this was implemented solely on a subset of extracted blocks. The CO_{2eq} emissions associated with comminuting a ton of ore can be calculated using Bond's law and Equation 6.

$$C_{Crushing} = \left(3.6 \times 10 \times W_i \times \left(\frac{1}{\sqrt{P_{cr}^{80}}} - \frac{1}{\sqrt{F_{cr}^{80}}}\right)\right) \times \zeta \tag{6}$$

2.2. Carbon Pricing

Climate change possesses the capacity to impact mining operations, posing risks across environmental, social, and financial dimensions. These risks have the potential to affect operations directly and can also exert an influence on a company at the corporate level due to heightened investor concern and expectations. The primary energy sources utilized in the examined mining operations include diesel, explosives, and electricity, serving various purposes within the mining activities. In assessing the financial risk associated with the potential implementation of a carbon price, the scope outlined in section 2.1 has been considered.

The examined facility is situated in the Middle East and encompasses open-pit mines, a concentrator, and a hydrometallurgy plant. In this investigation, the analysis concludes with the comminution of ore material, and downstream processes are not taken into account. The International Energy Agency (IEA) (2021) has provided a range of possible carbon prices depending on the country and year, as outlined in Table 2. The examination carried out in this paper begins with an assumed average carbon price of $30 per ton and is situated in the Middle East, categorized as a developing country (International Energy Agency, IEA, 2021).

Table 2. USD Carbon Pricing Model (International Energy Agency, IEA, 2021)

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

2.3. Integrating Environmental Costs

In this investigation, we initially assessed the energy consumption of individual blocks by considering the underlying physical processes. Subsequently, we computed the GWP derived from the determined energy consumption. The process of incorporating the CO_{2eq} price into the financial analysis is depicted in Figure 2. In the initial phase, the primary mining operations are categorized into activities that are applied universally to all blocks, irrespective of their destination, and those specifically carried out on blocks directed to the waste dump and crusher. This division is essential for accurately integrating carbon prices into the subsequent process without making approximations in carbon emissions and their related costs.

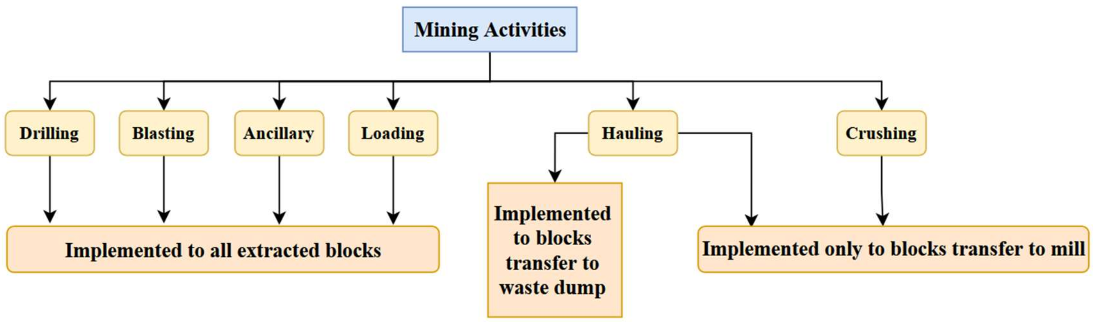

Figure 2. Schematic representation of the approach used to integrate CO2 costs into the mine plan.

Due to this rationale, we opted to combine drilling, ancillary tasks, blasting, and loading. All blocks chosen for extraction undergo these four mining activities. Transporting the extracted material from the pit is unquestionably an essential operation, generating a significant portion of the total emissions directly correlated with the distance covered by the haul trucks to convey the material to either the designated crusher or waste dump. Hence, we distinguished between emissions associated with block transportation to the crusher and those to the waste dump, depending on the respective destination locations. Finally, the crushing phase, involving the reduction of solid materials from a certain average particle size to a smaller average particle size using a crusher, is exclusively conducted on extracted material categorized as ore.

2.4. Integrated Framework for Long-term Mine Planning

Long-term mine planning entails the strategic development and implementation of plans to optimize the value of mineral resources over their entire life cycles. This process involves a comprehensive consideration of geological, technical, economic, environmental, and social factors, incorporating assessments of uncertainties and operational risks. Leveraging sophisticated tools such as strategic options analysis, mine life planning, optimization models, simulations, and scenario planning, professionals evaluate and compare different options to identify the most suitable ones aligned with project constraints. The significance of long-term mine planning lies in its crucial role in ensuring the sustainability, profitability, and safety of mining operations, all while adhering to industry regulations and standards.

When it comes to long-term mine planning, it is crucial to develop strategies that go beyond short-term economic gains and prioritize environmental concerns and sustainable practices. Our approach introduces a novel framework that seamlessly integrates carbon pricing into long-term planning processes. Traditional mine planning often prioritizes economic benefits without considering the environmental costs involved. Our framework lies in systematically incorporating carbon pricing, making sure that the costs associated with CO2 emissions are essential factors in decision-making throughout the entire lifespan of the mine.

Within this integrated framework, we embark on an analysis of environmental costs through two groundbreaking approaches. The first approach involves minimizing the environmental cost, strategically aligning with the growing imperative for eco-friendly mining practices. This signifies a paradigm shift, acknowledging that minimizing the ecological footprint is as crucial as maximizing economic returns. The second approach introduces a cutting-edge method of maximizing adjusted NPV, where the economic value of each mining block is intricately linked with its associated carbon cost. This dual focus on economic and environmental factors represents a groundbreaking advancement in the field of long-term mine planning, offering a comprehensive strategy that pioneers sustainability in the mining industry.

2.4.1. Minimization of Environmental Costs

The integration of Mixed Integer Linear Programming (MILP) in long-term mine planning offers a unique approach to reduce environmental costs. MILP, a mathematical optimization technique, is crucial in making sustainable mining decisions. In this scenario, by using a MILP model to formulate the mine planning problem, the focus shifts from maximizing economic returns to minimizing the environmental impact, particularly in relation to carbon emissions. This innovative framework allows for the consideration of environmental concerns as essential factors in the optimization process, enabling a comprehensive evaluation of mining strategies that balance economic viability with ecological responsibility. The outcome is an optimized long-term mine plan that not only maximizes economic benefits but also actively addresses environmental impacts, demonstrating a forward-thinking approach to mining operations.

Equations 7 to 13 illustrate the MILP model for long-term planning. The integrated framework was developed for the purpose of long-term planning of the ore body. The blocks in the block model are scheduled directly on an annual basis, adhering to operational constraints (e.g., annual extraction or plant capacity) as well as desired constraints, such as product grade. The ultimate objective of the optimization process is to minimize the environmental costs associated with the mining activities of the project. The decision variable x_id^t is assigned a value of one if block i is extracted during time period t and send to destination d, and zero otherwise. C_i represents the associated environmental costs for block i. Table 4 contains all the required set and parameters for integrated model.

$$Min \sum_{d=1}^{D}\sum_{t=1}^{T}\sum_{i=1}^{I}\frac{C_i}{(1+\varepsilon)^t}x_{id}^{t}b_i, \qquad x_{id}^{t}\epsilon\{0,1\} \tag{7}$$

$$\sum_{d=1}^{D}\sum_{r=1}^{t}x_{jd}^{r}-\sum_{d=1}^{D}x_{id}^{t}\geq 0, \quad \forall\, t=1,\dots.,T; i\in I; j\in\ I_{pi} \tag{8}$$

$$M_{el}^{t}\leq\sum_{i=1}^{I}b_i\,x_{id}^{t}\leq M_{eu}^{t}, \quad \forall\, t=1,\dots.,T, d=1,\dots,D \tag{9}$$

$$M_{pl}^{t}\leq\sum_{i=1}^{O}b_i\,x_{id}^{t}\leq M_{pu}^{t}, \quad \forall\, t=1,\dots.,T, d=1,\dots,D \tag{10}$$

$$\sum_{i=1}^{O}b_i\,x_{id}^{t}(g_i-g_u^t)\leq 0, \quad \forall\, t=1,\dots.,T, d=1,\dots,D \tag{11}$$

$$\sum_{i=1}^{O}b_i\,x_{id}^{t}(g_i-g_l^t)\geq 0, \quad \forall\, t=1,\dots.,T, d=1,\dots,D \tag{12}$$

$$\sum_{d=1}^{D}\sum_{t=1}^{T} x_{id}^{t} \leq 1, \quad \forall\, i = 1, \ldots, I \tag{13}$$

In the presented integrated model, the objective function (Equation (7)) aims to minimize the environmental costs associated with mining activities. The environmental emissions are determined in Section 2.1, which analyzes the necessary processes for each block. The environmental emissions are then translated into financial terms with consideration of carbon pricing, and finally discounted over time using the discount rate (ε). Equation (8) represents the slope stability constraint, ensuring that if block j is a prerequisite for extracting block i, block j must be extracted before block i to maintain mining structure integrity and prevent destabilization. Equation (9) outlines maximum and minimum extraction capacities, ensuring that the total tonnage of waste and ore blocks extracted adheres to the mining extraction capacity. Equation (10) regulates the input feed to the processing plant, constrained by the minimum and maximum processing capacities for each time period. Additionally, Equations (11) and (12) establish grade constraints for the processing plant, ensuring that the weighted average grade of the processed ore stays within specified limits. According to Equation (13), each block can be extracted at most once.

Table 3. Sets and parameters of integrated framework.

Term	Description
$\boldsymbol{t}$	The set of time period, t = (0, 1, …, T)
$\boldsymbol{i}$	The set of extraction blocks, *i* = (0,1,…, I)
$\boldsymbol{d}$	The set of block's destination, d = (0, 1, …, D), where d=0 and d=1 denote waste and ore, respectively
$\boldsymbol{I_{pi}}$	The set of blocks that need to be extracted before block *i*
$\boldsymbol{M_{el}^{t}}$	The minimum extraction capacities
$\boldsymbol{M_{eu}^{t}}$	The maximum extraction capacities
$\boldsymbol{M_{pl}^{t}}$	The minimum processing capacities
$\boldsymbol{M_{pu}^{t}}$	The maximum processing capacities
$\boldsymbol{g_{i}}$	The grade of block *i*
$\boldsymbol{g_{u}^{t}}$	The maximum required grade for processing
$\boldsymbol{g_{l}^{t}}$	The minimum required grade for processing
$\boldsymbol{b_{i}}$	The tonnage of block *i*

2.4.2. Maximization Adjusted NPV

In traditional study, long-term mine planning approaches were employed with the primary objective of maximizing the NPV of the mining operation. NPV functions as a critical financial indicator, signifying the distinction between the present value of cash inflows and outflows throughout the mine's operational lifespan. Within the model, the objective of maximizing NPV is succinctly captured by Equation (14), which considers a range of factors including revenue derived from ore extraction, operational costs, and the discount rate. V_i denotes the economic value of block i.

$$Max \sum_{d=1}^{D}\sum_{t=1}^{T}\sum_{i=1}^{I} \frac{V_i}{(1+\varepsilon)^t} x_{id}^{t} b_i, \quad x_{id}^{t} \epsilon \{0, 1\} \tag{14}$$

Furthermore, the second phase of the MILP approach involves maximizing the Adjusted NPV, a nuanced measure that intricately links the economic value of each mining block with its associated carbon cost. Adjusted NPV considers the environmental impact of mining activities by incorporating the costs associated with carbon emissions into the traditional economic assessment (Equations 15 and 16). AV_i denotes the adjusted economic value of block i.

$$AV_i = V_i - C_i \quad \forall\, i = 1, \ldots, I \tag{15}$$

$$Max \sum_{d=1}^{D} \sum_{t=1}^{T} \sum_{i=1}^{I} \frac{AV_i}{(1+\varepsilon)^t} x_{id}^t b_i, \qquad x_{id}^t \epsilon \{0, 1\} \tag{16}$$

Generally, the integrated approach recognizes the importance of environmental responsibility in long-term mine planning, as decision-makers seek a balanced strategy that not only maximizes economic returns but also minimizes the ecological footprint. By concurrently optimizing both economic and environmental facets, the MILP model provides a comprehensive framework for sustainable and responsible mine planning.

3. Results

In this segment, we put into action the innovative integrated framework, considering two primary scenarios: one aimed at minimizing environmental costs and the other at maximizing adjusted NPV. The execution utilized the Python® programming language [28] and the CPLEX® solver [29]. All experiments were applied on a Windows 11 workstation featuring an AMD Ryzen 7 5800H CPU and 16GB of RAM. We applied the developed integrated framework to a practical case study involving an open-pit iron mine in Iran to verify and assess the developed integrated framework. The reserve modeling, planning activities, and long-term production planning were based on drill-hole prospecting data. In this integrated framework, a 5-year plan inside a longer time project is considered. Figure 3 presents aerial images of the case study, along with the location of the crusher and waste dump. This image provides a clear view of the positions of the waste dump and crusher, illustrating their impact on the generated carbon dioxide and associated environmental costs. The determination of the distance of the *i*th block from the comminution plant or waste dump relies on data extracted from Table 4.

Figure 3. Aerial images of the case study, along with the location of the crusher and waste dump

To calculate the distance of each block, the distances between the block and its output point within the pit, considering its destination, are determined. Subsequently, the distance from that point to the center of the destination, whether it be the crusher or waste dump, is measured.

In this study, it is assumed that all models are applied within a predefined ultimate pit limit, and it is highlighted that the carbon tax will not alter this predetermined limit.

Table 4. Location of waste dump and crusher in the case study.

Destination	X	Y	Z
Waste dump	355647	3552027	1687
Crusher	357908	3551267	1774

3.1. Economic and Environmental Block

Figure 4 illustrates a three-dimensional representation of the metal content (Fe grade) for individual blocks within the deposit. Additionally, Figure 5 presents a three-dimensional model showcasing the environmental costs associated with the deposit's operations. This information was employed, as outlined in the methodology, to plan the excavation of the pit, determining the selection and order of blocks for extraction. The geological block model emphasizes the presence of high-value zones situated beneath the deposit, indicating the necessity to initially extract lower-grade material. The values of environmental cost blocks reveal a region with blocks incurring high costs to the right of the deposit base. This is partially attributed to the need for additional transportation to remove these blocks from the pit. Given that the waste dump is located on the left, these materials must be transferred there.

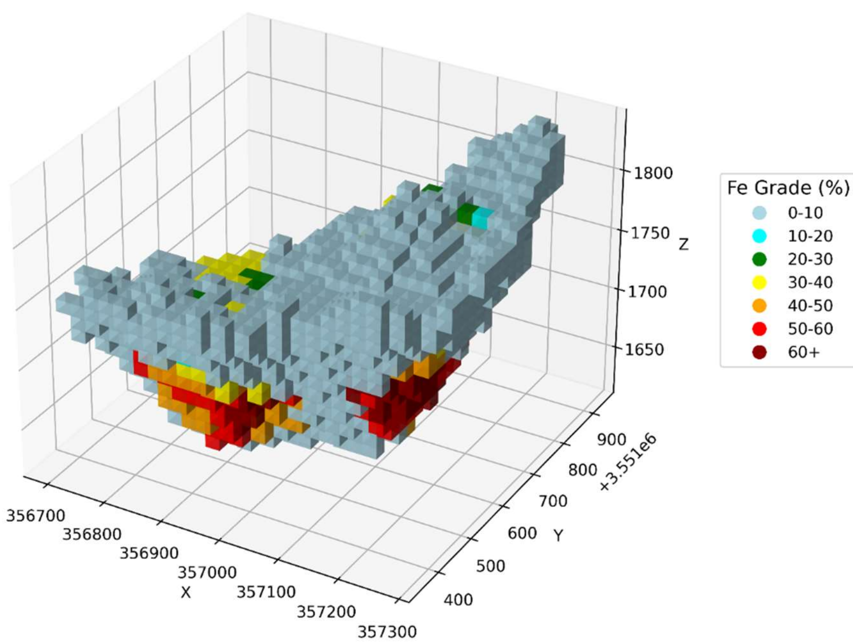

Figure 4. Grade distribution in block model.

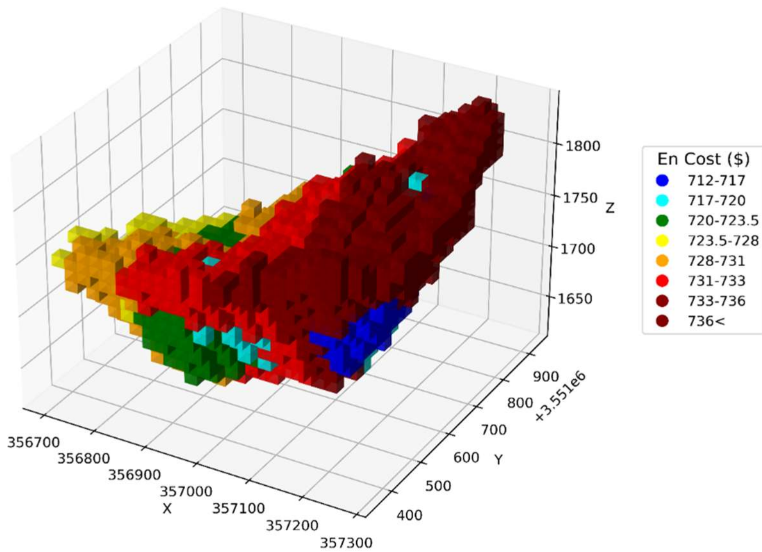

Figure 5. Environmental cost for each block.

Figure 6 illustrates the proportional carbon cost (environmental cost) associated with mining activities for two randomly selected blocks. The primary factor influencing carbon production is transportation, which has been modeled individually for each block. A growth in pit depth will intensify the carbon emissions generated by haulage due to extended cycle times, resulting in a higher amount of fuel needed to transport one ton of material. The ancillary needs account for 29% and 33% of the overall carbon emissions stemming from mining operations for waste and ore blocks, respectively. The ancillary equipment consisted of bulldozers for constructing waste dumps and handling various tasks, graders, water carts, compactors for maintaining haul roads, and front-end loaders for diverse activities.

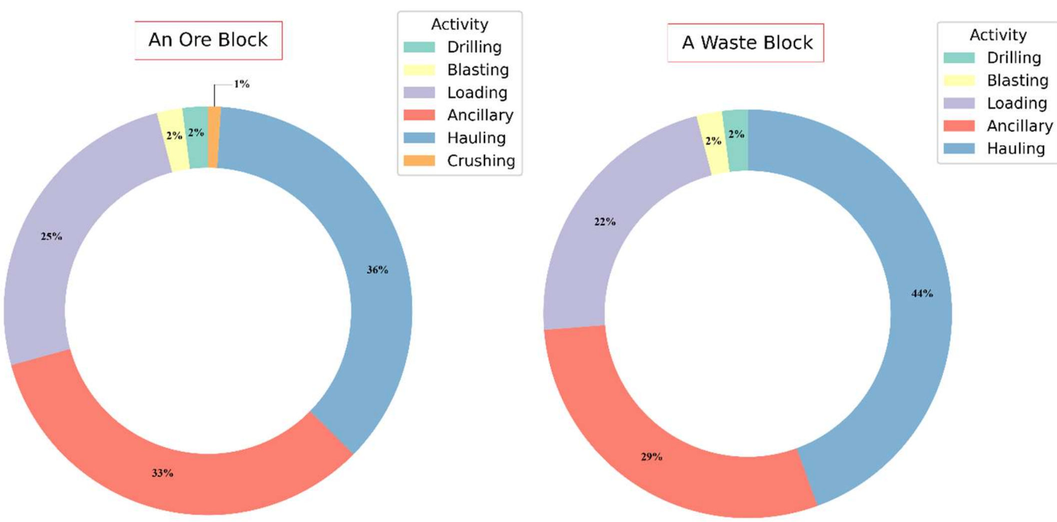

Figure 6. Percentage of carbon costs across mining activities.

Figure 7 illustrates the grade-tonnage distribution alongside the environmental emission distribution. This combined visualization offers readers insights into both the quality of the deposit and the relationship between grade and CO_2eq emission levels.

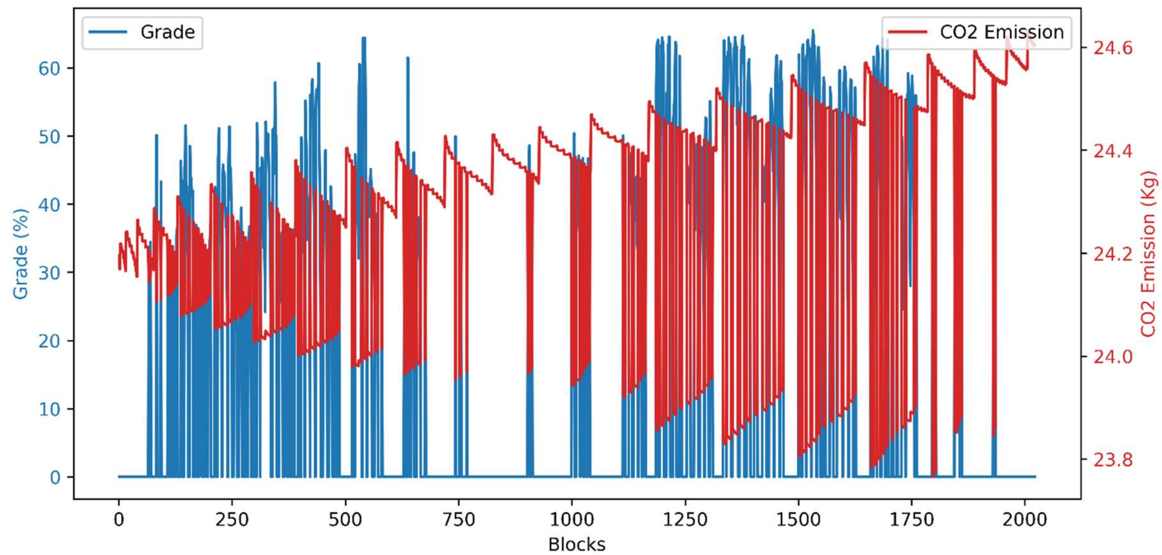

Figure 7. Grade and CO_2eq emission distribution for blocks.

3.2. Integrated Framework Results

The impact of carbon prices on the financial outcomes of mining operations has been examined. Initially, the assessment involves estimating the carbon-related costs associated with mining activities. Then, both scenarios were implemented in the mine schedule simulation by incorporating the carbon cost. In this context, Figure 8 illustrates the annual assignment of ore and waste based on each scheduling approach within the integrated framework. In the scenario focused on minimizing environmental costs, the integrated framework aims to defer blocks with elevated costs, particularly waste blocks associated with higher environmental impacts. By prioritizing the postponement of extraction for such blocks, the integrated framework aims to achieve its goal of reducing overall environmental expenses and promoting sustainable mining practices. Additionally, given the bottleneck nature of the plant's feed requirement, the framework ensures that the deferred actions do not compromise the plant's operational objectives, as depicted in Figure 8 by the presence of the red limit line. On the contrary, in the scenario focusing on maximizing adjusted NPV, the integrated framework aims to prioritize the extraction of the most valuable blocks in the initial periods while deferring the extraction of more costly blocks to subsequent periods. The inherent distinctions between these scenarios, both in nature and theory, result in varying block allocations across periods, thereby influencing GHG emissions, environmental costs, block sequencing, and financial outcomes.

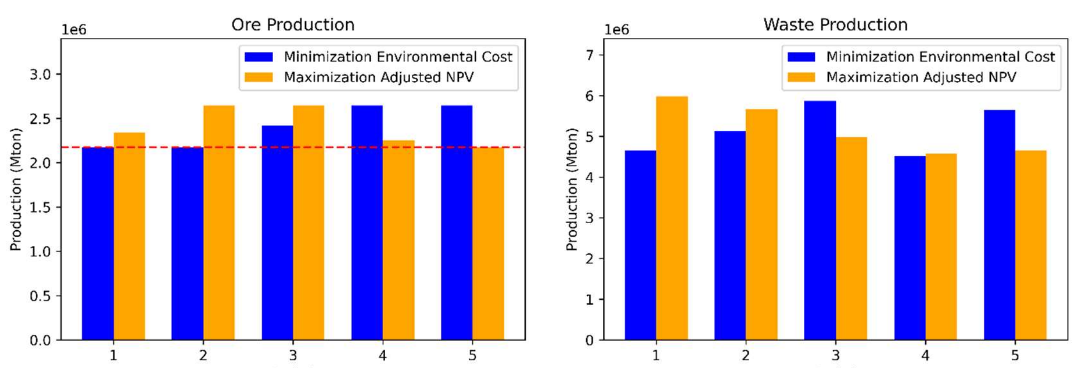

Figure 8. Detail of annual production (Ore and Waste).

The yearly CO_{2eq} emissions and the cumulative environmental costs linked to the two scenarios are illustrated in Figure 9. The yearly CO_{2eq} emissions in the maximization scenario exhibit an annual decline, aligning with the scenario's theoretical basis of maximizing adjusted NPV and block allocation. In contrast, the minimization scenario experiences a notably larger reduction in annual CO_{2eq} emissions and cumulative costs. In this scenario, the yearly emissions data reveals that CO_{2eq} emissions remain lower than those in the maximization scenario until period 3. Subsequently, there is an increase in annual emissions starting from period 3, followed by a reduction from period 4 onward. At the conclusion of the project, there is a notable decline, leading to a divergence in global warming impacts between the two scenarios. The values are 49030t and 44392t CO_{2eq}, representing a 9.5% difference for maximization of adjusted NPV and minimization of environmental costs, respectively. These CO_{2eq} emissions correspond to environmental costs of \$1.3M and \$1M for maximization of adjusted NPV and minimization of environmental costs, respectively.

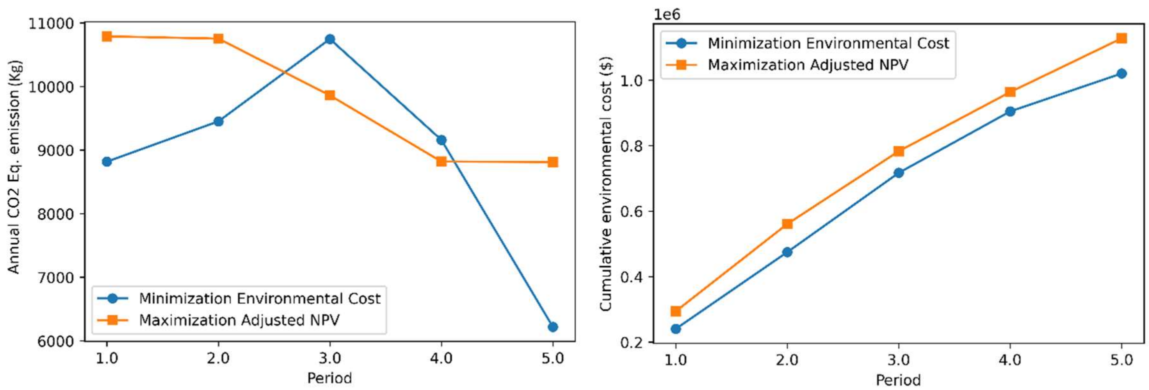

Figure 9. Annual CO_{2eq} emission (left) and cumulative environmental costs (right).

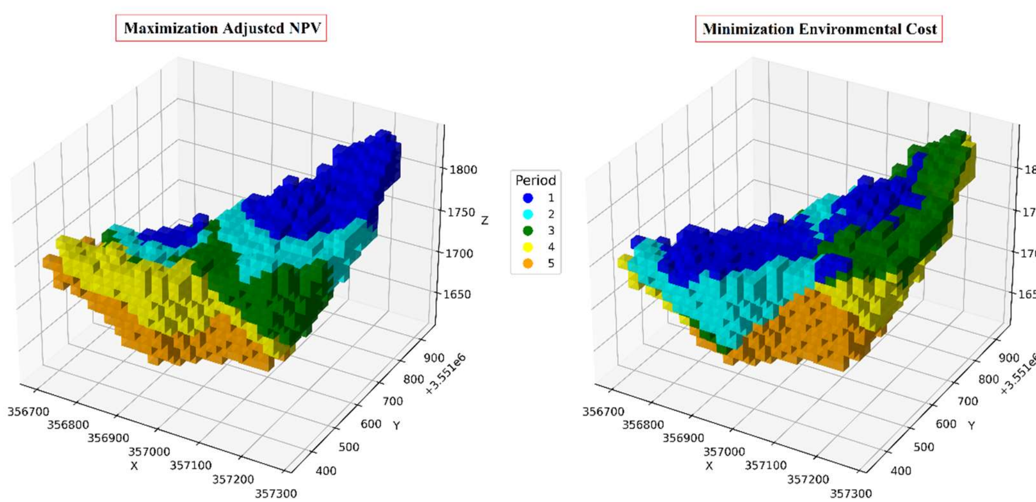

Figure 10. The block extraction sequencing in two scenarios.

As mentioned earlier, the blocks situated on the right side of the deposit exhibit lower grades and need to be transported to the waste dump, which is positioned on the left side of the deposit. Consequently, these blocks incur higher environmental costs compared to others. In this regard, Figure 10 illustrates the block sequencing in each scenario of the integrated framework. It is evident that the mentioned blocks are allocated to different periods in each scenario. In the minimization scenario, the integrated framework aims to assign blocks with lower costs in the early periods, in contrast to the maximization scenario, which prioritizes the extraction of more valuable blocks in the initial periods.

Clearly, alterations in block sequencing and their associated environmental costs have a notable impact on the net present value of mining operations, a key financial output that is thoroughly examined. Figure 11 depicts the annual and cumulative NPV of the mine plan for each scenario within the integrated framework. The graph highlights that, in the maximization scenario, the early periods exhibit a higher annual NPV, affirming the allocation of valuable blocks. Conversely, in the minimization scenario, the later periods show a higher annual NPV, attributed to an increased production rate and altered block sequencing.

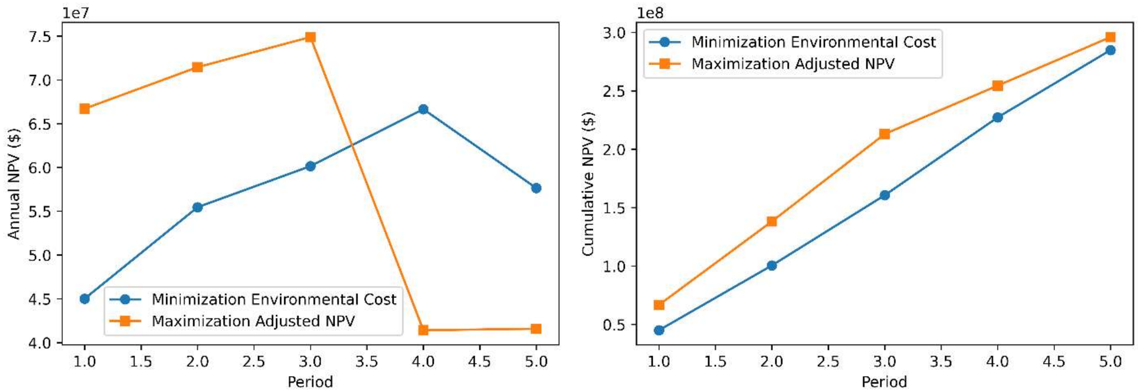

Figure 11. Annual NPV (left) and cumulative NPV (right) for two scenarios.

In general, Table 5 presents the results of the integrated framework for each scenario concerning CO_{2eq} emissions, environmental costs, and NPV. Additionally, Table 5 emphasizes the differences in the obtained results between each scenario. A positive value indicates that the minimization scenario achieves a higher value in those parameters, while a negative value implies the opposite. Based on the results, implementing the scenario aimed at minimizing environmental costs resulted in a reduction of approximately 10% in GHG emissions and environmental costs, while only reducing the adjusted NPV by approximately 4% compared to the scenario focused on maximizing adjusted NPV.

Table 5. Results of integrated framework in two scenarios.

Scenario	Parameter	Period					Total	
		1	2	3	4	5	Value	Dif
Maximize NPV (Base)	CO2eq (Kt)	10.97	10.9	9.77	9.57	9.13	50.4	+2.86
	En costs (M$)	0.299	0.27	0.22	0.196	0.17	1.16	+5.45
	NPV (M$)	67	71.7	75.1	41.6	41.7	297	+0.3
Maximize adjusted NPV	CO2eq (Kt)	10.8	10.8	9.86	8.82	8.81	49	-
	En costs (M$)	0.294	0.267	0.222	0.181	0.164	1.1	-
	NPV (M$)	66.7	71.4	74.9	41.4	41.6	296	-
Minimize environmental cost	CO2eq (Kt)	8.82	9.45	10.7	9.16	6.22	44.4	-9.46
	En costs (M$)	0.240	0.234	0.242	0.188	0.116	1.02	-9.52
	NPV (M$)	45	55.5	60.1	66.6	57.6	285	-3.75

Stripping ratio (SR) serves as a critical indicator in mine planning, directly influencing operational efficiency and resource utilization. Figure 12 illustrates the annual stripping ratios for scenarios.

The Max Adjusted NPV scenario shows a slight increase in stripping ratios in the first two periods, followed by a decrease in later periods. In contrast, the Min Environmental Cost scenario displays a relatively stable trend with minor fluctuations. This indicates that while the Max Adjusted NPV scenario may have higher initial stripping ratios due to environmental factors, it eventually stabilizes, unlike the consistent stripping ratios seen in the Min Environmental Cost scenario.

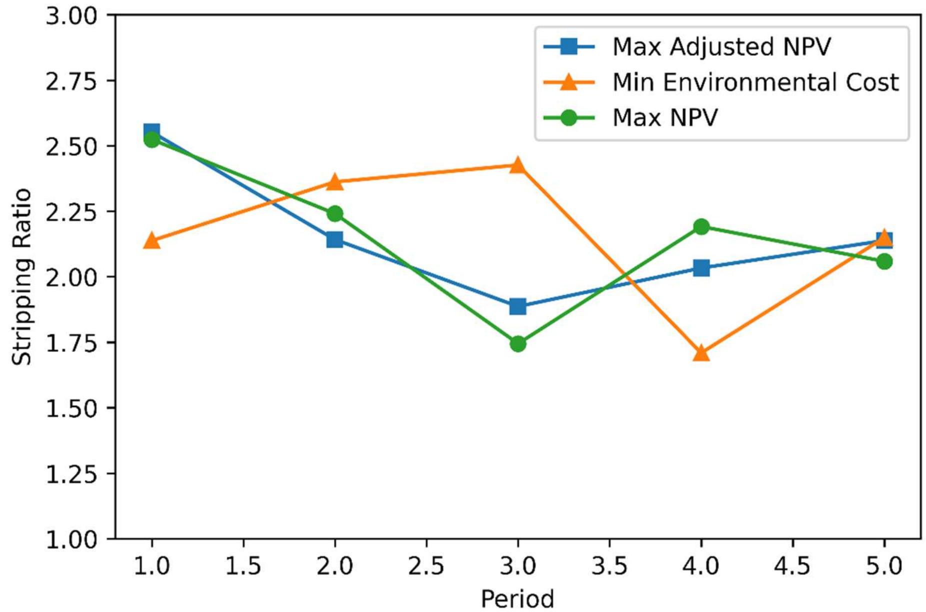

Figure 12. Comparison of stripping ratios for scenarios over time.

3.3. Sensitivity Analysis

Sensitivity analyses have been conducted to quantify the correlation between model performance and crucial parameters. The outcomes of both the minimization of environmental costs and maximization of adjusted NPV scenarios in the integrated framework rely on certain parameters, and any variations in these parameters can influence the application of these models to open-pit mining operations. Therefore, it is essential to study the effects of such variations. The sensitivity analysis relies on the MILP model within the integrated framework, aiming to maximize NPV and illustrates the impact of carbon pricing on the results. Therefore, an alternative schedule is generated using identical parameters to those used in the schedule as mentioned earlier, with the only difference being the carbon pricing set at $15/t, $30/t, $45/t, and $60/t.

As the carbon price rises, it imposes additional costs on the economic value of each block, potentially leading to a decline in financial targets. Figure 13 illustrates the annual NPV risk profile for mining operations, revealing variations compared to Figure 11. Consequently, elevating the carbon price may not enhance project economics but can contribute to advancing sustainability and green initiatives.

Figure 14 illustrates the sequencing of block extraction for NPV, adjusted NPV-30$, and adjusted NPV-60$ methodologies. While there are variations in the generated mine schedules, they generally designate the same areas for mining during corresponding time periods. As anticipated, minor distinctions are likely to diminish when practical schedules are implemented. The most notable difference is observed in periods two (cyan) and three (green).

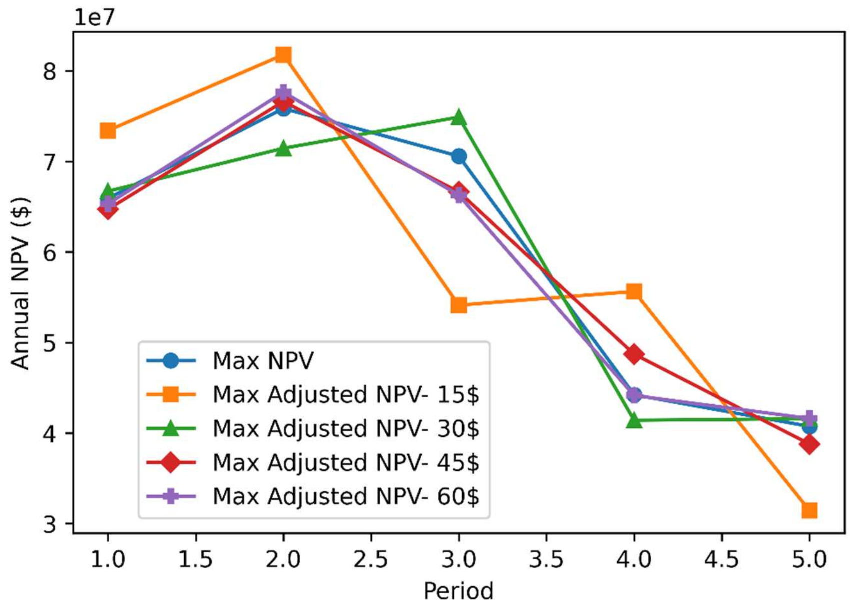

Figure 13. Annual NPV risk assessment for the mine schedule under varied carbon pricing.

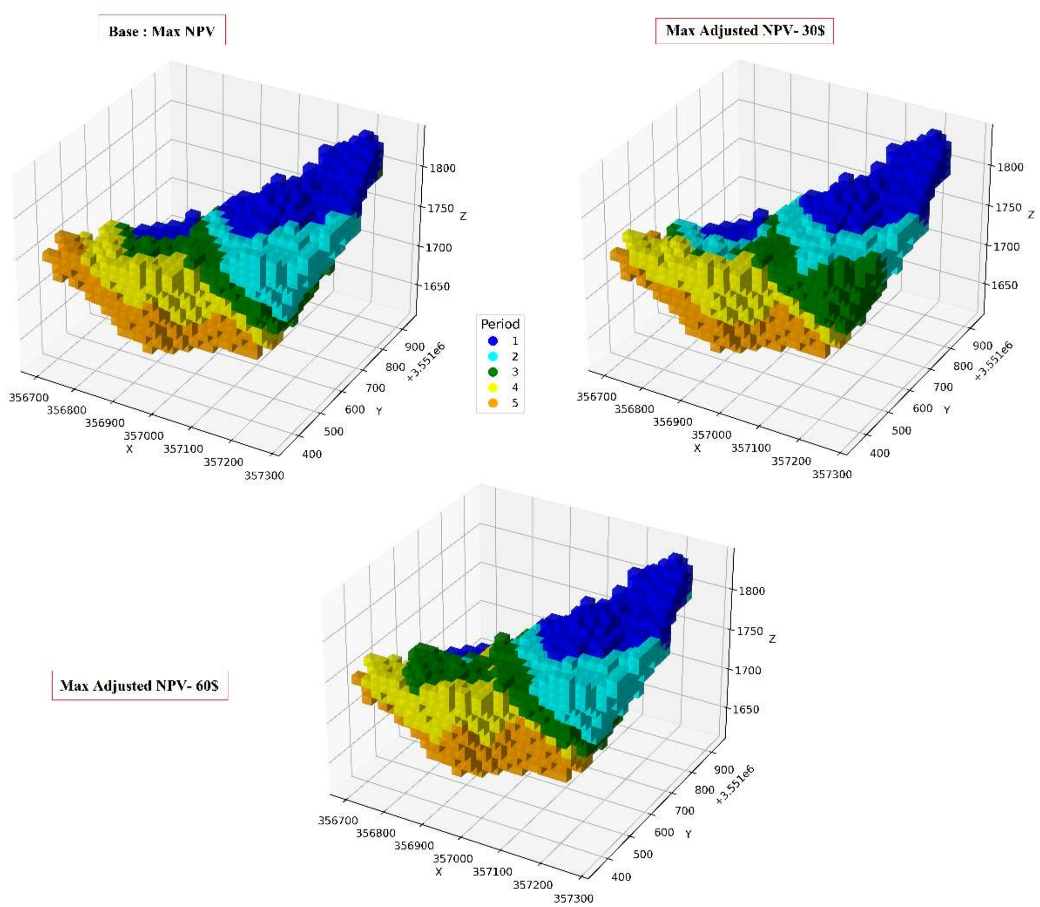

Figure 14. The block extraction sequencing for NPV, adjusted NPV-30$, and adjusted NPV-60$.

4. Conclusion

In conclusion, the presented novel framework for integrating environmental costs and carbon pricing in open-pit mine plans represents a significant step towards promoting sustainability and green practices in the mining industry. The comprehensive methodology, encompassing emission quantification and a sophisticated long-term mine planning approach, provides a holistic understanding of the environmental impact associated with mining activities. Through two distinct scenarios—minimizing environmental costs and maximizing adjusted NPV— the framework demonstrates its versatility in addressing both economic and ecological considerations. The results underscore the framework's effectiveness, showcasing its potential to significantly reduce carbon emissions and environmental costs while still maintaining a competitive economic performance. The sensitivity analysis further emphasizes the adaptability of the framework to varying carbon pricing scenarios, reaffirming its robustness in navigating the dynamic landscape of open-pit mining operations.

Considering the mounting pressure on the mining industry to embrace sustainable practices, this framework presents an innovative solution that surpasses conventional economic factors. By effectively incorporating environmental expenses into the long-term planning of mines, decision-makers can make well-informed decisions that prioritize both economic feasibility and environmental accountability. The demonstrated success of this framework in a practical case study, set in an open-pit iron mine, highlights its applicability and potential for widespread adoption across diverse mining operations. In essence, the pursuit of sustainable and green mining practices in open-pit mines necessitates innovative frameworks like the one presented here. By bridging the gap between economic objectives and environmental concerns, this approach contributes to a more balanced and responsible future for the mining industry.

The current framework proposed provides a thorough examination of how environmental considerations can be integrated into mine planning. However, there are certain limitations that need to be addressed in future research. One key issue is the use of a fixed ultimate pit limit in all models, which requires further investigation into the effects of carbon pricing on different aspects of mining operations, including mine size and profitability. It is also crucial to incorporate other important environmental factors like water usage, dust, vibrations, and disturbance footprint into mine planning models. To promote sustainable mining practices and ensure environmental sustainability and community well-being, it is crucial to consider these key factors. By incorporating these factors into our analysis, we can enhance our understanding of the environmental impacts of mining activities and make better decisions moving forward.

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